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Estimation of Norwegian Asphalt Surfacing Lifetimes Using Survival Analysis Coupled with Road Spatial Data

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Abstract: Combinations of different factors and their relative importance have a mixed effect on the longevity of pavements, which are essential to be understood to enhance long-term maintenance planning. This study used spatial road data from Norway followed by integrating temporal-spatial and statistical analyses to show a potential approach to estimate the lifetimes of asphalt surfacing. For the statistical part, a stratified Cox proportional hazard model was used to understand the relationship between longevity of surface mixtures and different factors, while avoiding having predefined assumptions rooted in deterministic modeling. In addition, rutting was used as the response variable to determine distress-specific asphalt surfacing lifetimes and to handle censored data. Inclusion of rutting as the response variable showed that the median technical lifetime of asphalt surfacing is about 2 years shorter than that of the maintenance activity records. The results showed the significance of each covariate; however, aggregate nominal maximum size and heavy traffic volume were consistently the significant covariates across the studied traffic classes. In addition, the results were fitted to reference categories in each covariate to show a practical approach to interpret absolute values of lifetimes from a survival table. **DOI: 10.1061/JPEODX.0000115.**

Introduction

Recent advances in the availability of road data and the inclusion of spatial dimensions have opened up a greater opportunity for road infrastructure assessment. In the domain of pavement management systems (PMS), spatial and temporal analysis of pavement conditions assists in providing a more in-depth understanding of pavement deterioration propensity and the optimization of maintenance planning (Chen et al. 2014). GIS have been shown to constitute a potentially useful tool for temporal-spatial analysis (Pantha et al. 2010). They provide a platform for data visualization, thematic mapping, and merging data from different databases, as well as for storing and exchanging data for postprocessing purposes (Osterbring et al. 2016). In this context, a number of studies were conducted to answer various challenging questions in the area of transportation using GIS-aided statistical analyses (Ayalew and Yamagishi 2005; Li et al. 2007; Wang and Kockelman 2007; Morgenstern et al. 2008; Dai 2012; Jaafari et al. 2015; Lee et al. 2015), and some researchers used GIS more specifically in pavement management studies (Obaidat and Al-kheder 2006; Pantha et al. 2010; Chen et al. 2014).

The advantage of introducing GIS in PMS is that it allows a potential procedure for creating a greater understanding of pavement behaviors (Shahin et al. 1998). This approach has already been applied by the Norwegian PMS. However, the estimation of pavement lifetimes in the Norwegian PMS lacks the incorporation of statistical methods to show the nonlinearity of pavement deterioration. This means that the Norwegian PMS uses a linear prediction model based on two surveyed data items, longitudinal and transverse unevenness, to forecast the time of intervention (Gryteselv et al. 2001; Hyggen et al. 2010; Romanowska 2012; Johansen and Gryteselv 2015). The prediction model connects the first (when the pavement was newly laid) and the most recent measured values in the surveyed data. The created linear trend is extended until it meets the maximum allowed condition to determine the time for intervention in coming years. However, this forecasting approach does not take into account the nonlinear deterioration of road pavements due to the influence of various factors such as climate, driving pattern, structural composition, thicknesses of each pavement layer, traveled-way width, and the vertical and horizontal profile of the road geometry.

Various statistical methods have been used and suggested by previous authors (Prozzl and Madanat 2003; Wang et al. 2005; Ker et al. 2008; Do 2011; Luo 2013; Gao et al. 2012; Svenson 2014; Han et al. 2014; Giang and Pheng 2015; Karlaftis and Badr 2015; Dong et al. 2015; Rajbongshi and Thongram 2016) who attempted to estimate pavement lifetimes with a high level of reliability. Among the applied statistical methods, survival analysis, also known as time-to-event analysis, has gained attention in the last few decades because of its ability to assess the nonlinearity of pavement failure times and to handle censored data over an analysis period.

Survival analysis has a long history of application in the field of epidemiology for studying the time of an event; various models have been used to predict the occurrence probability of an event of interest. In the area of road infrastructure, survival analysis has been used for various purposes and to draw inferences using different duration models, i.e., parametric, semiparametric, and nonparametric, to estimate the probability of failures. The nonparametric model is often preferred because of its simplicity and because it does not involve assumptions about the baseline hazard

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distribution. This model was used as a standalone model in some previous studies (Destefano and Grivas 1998; Eltahan et al. 1999; Gharaibeh and Darter 2003; Dehghan et al. 2008) using the product-limit estimator, also known as the Kaplan–Meier estimator, to determine failure time (Moore 2016). Despite the flexibility and simplicity of nonparametric models, they cannot easily incorporate different explanatory variables, i.e., covariates, in their estimations and cannot explain the underlying causes of failure.

Parametric survival analysis follows defined baseline hazard distributions to estimate the survival time, and thus it is possible to handle data noise, and multivariable analysis is supported. Such a model has been implemented extensively in deterioration modeling using different functions, such as exponential, Weibull, lognormal, and log-logistic (Yang et al. 2013). Wang et al. (2005) incorporated generalized gamma distribution to estimate the survival time of flexible pavements by considering fatigue cracking as the response variable. Do and Kwon (2010) used series of parametric probability distributions to estimate pavement lifetime, and their results showed that lognormal distribution appropriately describes the data. Similarly, Loizos and Karlaftis (2005) determined that lognormal distribution appropriately describes the initiation of cracking in a pavement surface. Yang (2009) used log-logistic distribution for the model estimation to overcome the limited explanatory variables registered in the PMS data at the network level. In a study conducted by Dong and Huang (2014), survival analysis with the Weibull hazard function was used by means of utilizing various explanatory variables to estimate the effect of crack initiation on resurfaced asphalt pavement.

Although parametric models were preferred by the authors of previous studies, because they create smooth survival curves, the reliability of the results estimated by these models strongly depends on the selection of appropriate distributions (Li 2005). Verification can be achieved via graphs and likelihood testing. However, the results are tightly bound to the availability and nature of the data, which sometimes makes it difficult to find appropriate fits, in particular for cases that cannot be explained by simpler distributions.

The semiparametric statistical model is located somewhere between the two previous duration models, because it does not make prior assumptions about baseline hazard distribution and can incorporate explanatory variables into the estimation. Svenson (2014) implemented a stratified Cox proportional hazard (PH) model to estimate the lifetime of Swedish pavement concerning seven explanatory variables. Shin (2006) used the Cox PH model to estimate the initiation of cracks in the pavement in the AASHO road test data. Despite the flexibility of semiparametric models, the results obtained from the model show its relative approach for estimating survival probability. This implies that the model uses partial likelihood estimators to estimate the baseline hazard. To overcome the limitation, it is hence necessary to fit the results from the model to baseline categories in each explanatory variable to estimate absolute differences.

This study estimated the lifetime of asphalt surfacing, i.e., the time from laying a new surface layer until the in-service layer fails, for selected road categories in Norway using GIS-based survival analyses. In doing so, this study applied data mining and performed GIS-based manipulation of some selected road data before the survival analyses. Only open road infrastructure was evaluated, and road tunnels and bridges were excluded from the area of investigation. These infrastructures were selected because the goal of the study was to investigate only pavement structures that meet certain design criteria. In addition, only three Norwegian road categories were selected: European, national, and county roads. These three road categories were chosen because the Norwegian Public Road Administration (NPRA) is the entity responsible for their planning, construction, operation, and maintenance (Stephansen 2017). The data obtained from the temporal-spatial analysis were then assessed by a stratified Cox PH model (Cox 1972) to estimate the lifetimes. The stratification was performed on asphalt surfacing mixture types in four different annual average daily traffic (AADT) classes. In addition, six explanatory variables were selected to investigate their effects on the longevity of asphalt surfacing. The selected explanatory variables were posted speed limit, bearing capacity class, aggregate nominal maximum size, climate zone, heavy traffic volume (AADT-t), and asphalt content usage.

Methodology

Data Source

In this research, the road data were collected from the Norwegian Road Database (NVDB), primarily developed by the NPRA. Since 2006, the NVDB has been used as the central system to compile digital road information. The database covers various road objects and relationships between the objects, such as operation and maintenance, accessibility, and location of roadways. The entire road information in the database is structured on the linear referencing system (LRS) (NPRA 2010). The system follows the network topology on a node-link structure that covers both local and time information for nodes and lines in the network. Local information captures geographic information, whereas time information declares the validity of the road information.

Currently, the NVDB covers more than 93,000 km of Norwegian roads, and there are different mechanisms for fetching historical road data from the database, such as NVDB 123, NVDB analysis, NVDB application programming interface (API), and Transport Network Engine (TNE).

TNE, NVDB 123, and NVDB API were used to collect the road data for this study. This was because of certain restrictions in each platform; the use of the three engines in parallel and different analytical solutions compensated for their limitations. The data collection was conducted for three counties in Norway, i.e., Troms, Sør-Trøndelag, and Vest-Agder, and the following data were collected: registered asphalt surfacing, location of bridges and tunnels, road referencing, posted speed limit, bearing-capacity class, AADT, road width, and rut measurement.

This study considered a shorter assessment period than previous research (Svenson 2014) because road engineering, especially asphalt technology, has improved over the last few decades. In addition, more-accurate and more-precise road surveying equipment has been introduced since 2000 in Norway (Thodesen et al. 2012). Therefore, this study took into account only road information between 2000 (January 1, 2000) and 2017 (December 31, 2016) from the collected road data. Thus, only approximately consistent paving technologies were evaluated, and it was possible to take advantage of the more reliable rut measurement technologies used during the selected time frame.

Spatial Analysis

The NVDB database handles the issue of data validity using the Norwegian LRS system, which uses the geometric location and validity periods. These attributes map the geometry of each feature and address the length of time a feature is valid. The validity period is based on lower and upper registered dates presenting the start and end dates for each feature. If a feature is currently valid, the upper registered data show a date that is far into the future (i.e., 9999-12-31), whereas if the road feature is no longer valid the registered date is replaced by a termination date (e.g., 2009-10-03).

In addition, the NVDB database uses certain road referencing principals that assist in monitoring road spatial data. The referencing data are the skeleton of the road data on which the network data are based. Every time a change occurs in certain roads that affects their road referencing data, the data are reregistered in NVDB. In some cases, the changes might not show the same geometric length for cloned features because of lengthening or shortening of the road referencing length over the years.

For spatial location, the upper and lower validity dates were very critical for this research, because they made it possible to avoid counting a feature more than once; e.g., one feature might be cloned a few times, but with different lower and upper limits. Here, the theory behind the temporal-spatial analysis is based on a method that was explained extensively by Ebrahimi (2017). The method used sequential steps to explore the data and merged them using two commercial GIS software tools. The details of the work were given in Chapter 5 of Ebrahimi (2017), and are not discussed further in this paper.

Survival Analysis

The definition of Kleinbaum and Klein (2012) was used as the basis for the survival analysis in this study. Hereafter, T denotes the time of an event, which is a continuous nonnegative random variable, and t denotes any fixed value of interest for the random variable T. The survivor function is denoted $S(t)$, and gives the probability that an observation survives longer than the time t.

The survival analysis can be also written $S(t) = P(T > t) = 1 - F(t) = \int_t^\infty f(t)dt$, where $f(t)$ is the probability density function (PDF) and $F(t)$ is the cumulative density function (CDF). The hazard function is denoted $h(t)$, which can be expressed by

$$h(t) = \lim_{\Delta t \to 0} \frac{P(t \leq T < t + \Delta t | T \geq t)}{\Delta t} \tag{1}$$

This implies that $h(t)$ is the limit as Δt goes to zero of the probability of event T (where T is in an interval between t and $t + \Delta t$, given that T is larger than t), divided by Δt. In other words, the hazard function measures the risk of an event at a particular point in time, and the scale of its measure is between zero and infinity. The hazard function can also be stated as the function of the survivor and the PDF

$$h(t) = \frac{f(t)}{S(t)} \tag{2}$$

This study used a stratified Cox PH model to partition the data into strata based on the values of certain covariates. Data stratification yields an estimated survival curve for each stratum but still assumes that the effects of the covariates are constant for all strata. Such an approach hence incorporates the differences between strata by showing stratum-specific baseline hazards while estimating a single effect for each covariate (Kartsonaki 2016).

The hazard rate in a multivariable Cox PH model at time t that has s strata can be written

$$h_i(t|\mathbf{Z}_1, \mathbf{Z}_2, \ldots, \mathbf{Z}_p) = h_{0i}(t)e^{(\mathbf{Z}_1\boldsymbol{\beta}_1 + \mathbf{Z}_2\boldsymbol{\beta}_2, \ldots, \mathbf{Z}_p\boldsymbol{\beta}_p)},$$
$$i = \{1, 2, \ldots, s\} \tag{3}$$

Eq. (3) is the product of two quantities: the baseline hazard function, denoted h_0, and the exponential sum of $\mathbf{Z\beta}$, where $\mathbf{Z}$ is a matrix of covariates and $\boldsymbol{\beta}$ is a vector of regression coefficients measuring the impact of covariates. Also, p denotes the number of covariates.

The Cox PH model is incapable of handling left- and interval-censored data. In this study, left-censoring and interval-censoring were managed by incorporating transverse unevenness, i.e., rutting, as a response variable to overcome the limitations in the model.

The inclusion of rutting helps capture and resolve better the underlying limitations tied to the model. Because of the existence of annual surveying data, it was possible to follow up the condition of asphalt surfacing throughout the analysis period and detect left- and interval-censoring. In general, the vast majority of the selected roads in Norway, i.e., European, national, and county roads, are scanned at least once a year. However, it is not unusual that certain sections are surveyed more frequently than others in a calendar year. For instance, when a road undergoes a maintenance activity, the condition of the paved segment is scanned before and after the maintenance work to evaluate the quality of the finished work by comparison.

In addition, the inclusion of rutting made it possible to quantify technical lifetimes of registered asphalt surfacing. This was achieved by monitoring the rut propagation and setting conditions for the pattern and amount of rut depth. In other words, the lifetime of a newly laid homogeneous paved segment ended only if (1) a second surfacing was laid and the rut depth over the segment showed a substantial reduction, i.e., greater than or equal to 10 mm, in the propagation rut trend; or (2) a second surfacing was not yet laid, but the rut depth within the homogeneous paved segment reached or exceeded the maximum threshold values stated by the NPRA. The maximum allowed rut depth is 25 mm for roads with AADT equal to or lower than 5,000 vehicles and 20 mm for roads with AADT above 5,000 vehicles (NPRA 2014b).

Here, a homogeneous segment refers to a uniform lane in a traveled way with a length greater than or equal to 50 m and a consistent characteristic with respect to surfacing history, traffic volume (both AADT and AADT-t), asphalt surfacing mixture type, posted speed limit, bearing-capacity class, aggregate nominal maximum size, climate zone, asphalt content usage, and traveled-way width.

Summary of Data

Various paving layers might be placed on a segment of a road during a maintenance and rehabilitation (M&R) activity, which strongly depends on the condition of the road. In addition, it is possible that an asphalt wearing course and the layers underneath it (if they exist) were not paved within a few days of each other during an M&R activity, but instead, the wearing course was paved some months later because of various challenges, such as budgeting or seasonal changes. Furthermore, depending on the paving contracts, different warranty periods are determined by a road authority. A warranty period is usually 5 years in Norway and is based on rutting and roughness measurements. This study assumed that the overlaid roads that were observed during the 16-year analysis period should have lasted at least 2 years from the time they were paved. This approach helps to retain only overlaying information when evaluating the survival time of different asphalt surface mixture types.

Tables 1–3 summarize statistics of the variables generated from the GIS analysis in this research. The variables are AADT, asphalt surfacing mixture type, posted speed limit, bearing-capacity class, aggregate nominal maximum size, climate zone, heavy traffic volume (AADT-t), asphalt content usage, and traveled-way width. In total, 2,759 homogeneous segments were retained from the GIS analysis (Fig. 1).

Studded tires in cold climates, such as that in Norway, are a significant cause of pavement wear, resulting in longitudinal depressions in the wheel path of traffic lanes with high traffic volumes

Table 1. Quantitative variables for traffic volume, asphalt surfacing mixture types, and posted speed limits

Traffic volume				Type of asphalt surfacing			Posted speed limit		
AADT class	Range of AADT	Paved length (km)	No. of observations	Surfacing type	Paved length (km)	No. of observations	Posted speed limit (km/h)	Paved length (km)	No. of observations
1	≤300	—	—	AC-OB	304	1,189	50	118	595
2	301–1,500	—	—	AGC-OB	393	867	60	204	754
3	1,501–3,000	480	1,130	SA	21	68	70	127	419
4	3,001–5,000	154	564	SMA-OB	83	496	80	348	839
5	5,001–10,000	137	649	SMA-PMB	29	139	90	32	152
6	10,001–20,000	59	416	—	—	—	—	—	—
7	>20,000	—	—	—	—	—	—	—	—

Table 2. Quantitative variables for bearing capacity class, aggregate nominal maximum size, and climate zone

Bearing-capacity class			Aggregate nominal maximum size			Climate zone		
Bearing-capacity class	Paved length (km)	No. of observations	Nominal maximum size (mm)	Paved length (km)	No. of observations	Climate zone	Paved length (km)	No. of observations
T8-50	8	30	11	572	1,868	Troms	160	594
T10-50	820	2,729	16	257	891	Sør-Trøndelag	485	1,368
—	—	—	—	—	—	Vest-Agder	185	797

Table 3. Qualitative variables for traffic volume of heavy vehicles, asphalt content usage, and widths of traveled ways

AADT class	Heavy vehicle AADT (AADT-t)					Asphalt content usage (kg/m^2)					Traveled-way width (m)				
	Minimum	Median	Maximum	Mean	SDa	Minimum	Median	Maximum	Mean	SD	Minimum	Median	Maximum	Mean	SD
3	0	228	661	244	113	19	33	115	34	8	4	6.1	10.5	6.5	1
4	0	438	1,400	528	309	17	33	150	34	10	4.6	6.5	10.8	6.7	1
5	261	964	1,530	897	325	20	35	93	34	8	3.5	6.7	14	6.9	1
6	405	1,600	2,703	1,504	522	18	38	110	36	10	3.5	8.8	14	9.6	3

Note: SD = standard deviation.

(Snilsberg et al. 2016). Rutting has been found to be a weak indicator in the case of maintenance activities for low-traffic roads (Hyggen et al. 2010; Bjørklimark and Mandal 2016). This is because these roads are more susceptible to pavement distress other than rutting and they have longer lifetimes, sometimes longer than the period of assessment used in this study (NPRA 2014a). Hence, roads with AADTs between 1,500 and 20,000 vehicles were considered for the analysis. Because of the shortage of observations for AADTs above 20,000 vehicles, this research excluded these AADTs.

Traffic volume is a measure quantifying the number of vehicles passing certain measuring points on the road over a certain period. The quantified value is often given in units of AADT. The obtained traffic data in this study quantified the median value of the AADT over the cross section of a homogeneous paved segment. Based on an arbitrary choice, in this study surfacing segments that had an AADT difference between the median and the maximum values of the registered AADT greater than 20% were excluded. This condition was enforced to reduce bias and so that only homogeneous segments that had not experienced significant changes in traffic loading were included in the study. In addition, the clustering of different traffic volumes was arranged in the manner introduced in the Norwegian manual N200 (NPRA 2014a).

The most frequently used types of surfacing mixtures in the three counties were asphalt concrete (AC), asphalt gravel concrete (AGC), stone mastic asphalt (SMA), and soft-bitumen asphalt (SA). In general, various techniques can be used during asphalt production, which results in mixtures having different temperature ranges. Hot mix, warm mix, half-warm mix, and cold mix are the four typical asphalt mixes produced with different temperatures; they are sorted in descending order, respectively. The temperature for a hot mix is between 150°C and 180°C, whereas a cold mix is produced with unheated aggregate and bitumen (EAPA 2014). In this study, all surfacing mixtures were classified as hot-mix asphalt. In addition, only two binder types were considered: ordinary binder (OB) and polymer-modified binder (PMB). OB is a paving grade binder not positioned as a polymer-modified, emulsion, or foam binder. Polymers are used in the modification of bituminous binders; styrene-butadiene-styrene (SBS), styrene-butadiene rubber (SBR), ethylene vinyl acetate (EVA), or other polymers can be used (Yildirim 2007). SBS-modified binders were used in most of the pavements containing a modified binder in Norway (Saba et al. 2012).

Fig. 2 demonstrates the number of kilometers paved for each AADT class in each county. The chart demonstrates the total length of examined surfacing placed in each year for each county and AADT class. When the data were obtained from the database, very few paved kilometers were registered for 2016. It is common that the updating of historical data in the database is delayed.

According to the road design manual N100 (NPRA 2014d), the posted speed limits on Norwegian roads range between 30 and 110 km/h for main roads. The majority of main roads included in this study had posted speed limits of 60 or 80 km/h; however, roads might be assigned higher or lower posted speed limits over

J. Transp. Eng., Part B: Pavements, 2019, 145(3): 04019017

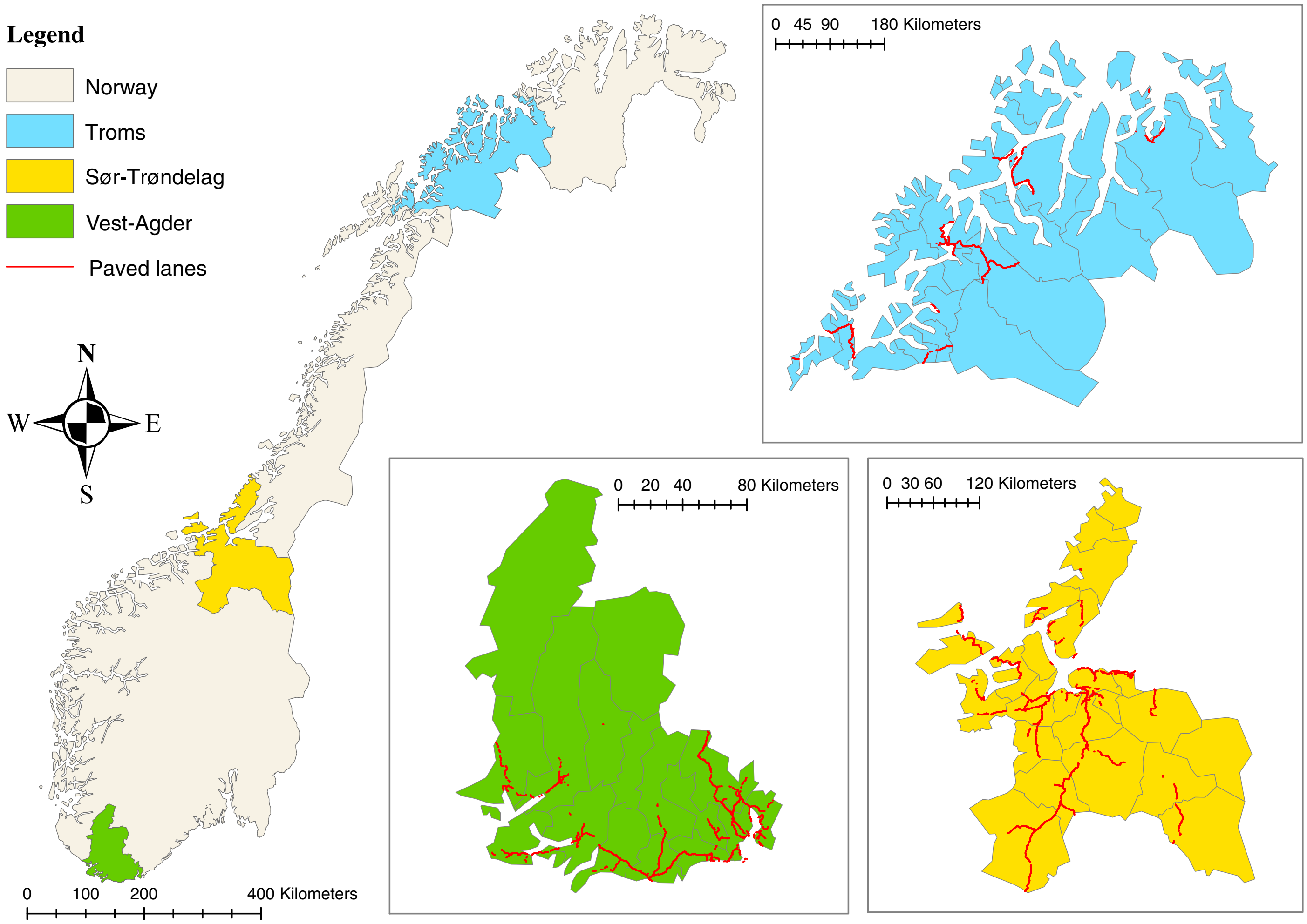

Fig. 1. Layout of examined paved lanes in Norway.

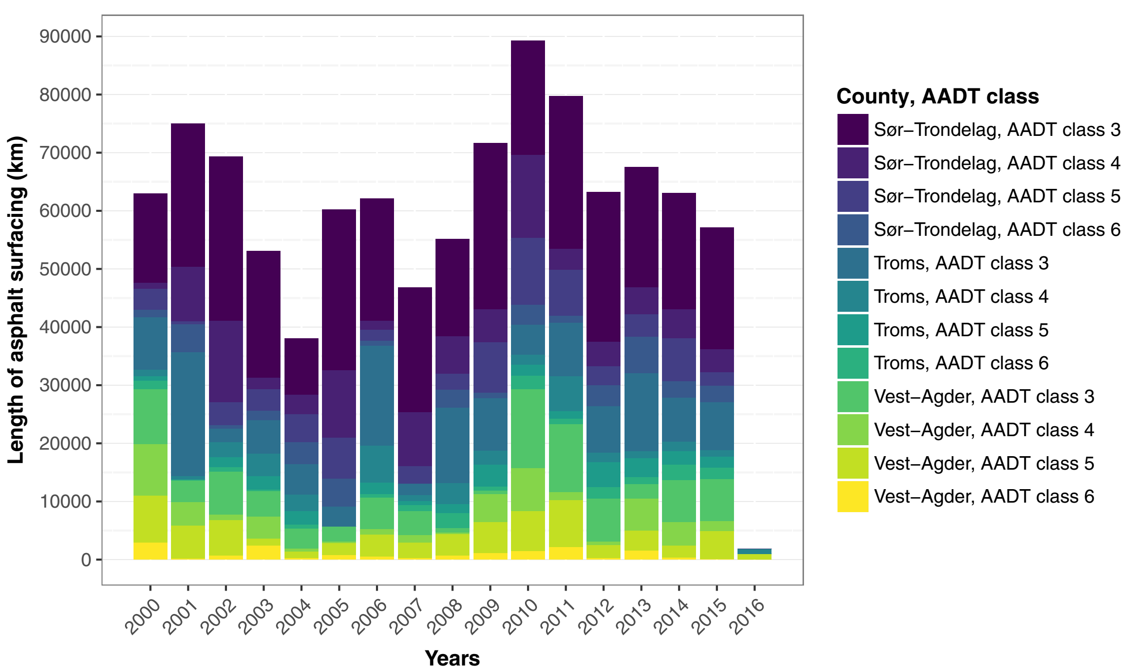

Fig. 2. Length of examined asphalt surfacing in each county with respect to corresponding annual average daily traffic class.

Table 4. Long-term statistics for average seasonal temperature and precipitation

Outdoor climate	County	Spring	Summer	Autumn	Winter
Average mean temperature (°C)	Troms	−2.3	8.6	0.1	−8.4
	Sør-Trøndelag	0.6	9.9	2.6	−5.6
	Vest-Agder	2.1	11.4	4.7	−3.7
Average precipitation (mm)	Troms	210	272	338	300
	Sør-Trøndelag	201	205	343	294
	Vest-Agder	246	326	477	399

the years because of their changing conditions and visibilities. In this study, only roads with constant posted speed limits throughout the years were considered.

Vehicle size and axle loads need to be limited to avoid structural deformation on roads. The bearing capacity of a road structure represents its structural strength to withstand traffic loads. In Norway, roads are grouped into different administrative load bearing-capacity classes. Each class shows the allowed axle load and maximum total weight in tons. Only two administrative bearing-capacity classes were included in this study: T10-50 and T8-50. T10-50, for instance, means that the axle load limit is 10 tons and the maximum allowed truck-trailer weight is 50 tons.

Aggregate nominal maximum size is used as an indication of the size of the sieve opening for the aggregate in a job mix. The aggregate nominal maximum size is the smallest sieve size through which the entire aggregate samples are able to pass. In this study, only two nominal maximum sizes were considered: 11 and 16 mm.

Climatic conditions in Norway, because of the existence of various microclimates, are distinctive. These variations in the climate, coupled with weak road structure and susceptible soil, have resulted in various types of structural fatigue in Norwegian roads. In addition, because studded tires are often used during the winter season, roads suffer from premature faults, typically caused by rutting, that trigger risks of accidents. This study investigated the effect of climate on pavement deterioration in three counties in Norway. The counties selected were Troms, Sør-Trøndelag, and Vest-Agder, and the climate zoning was based merely on their unique climatic conditions (Table 4) (Yr 2017; Norwegian Meteorological Institute 2017). This implies that the paved segments were grouped into the Troms, Sør-Trøndelag, and Vest-Agder climate zones.

In addition to the AADT, it was essential to know the number of heavy vehicles that passed on a road, because load repetition due to heavy traffic loading may lead to various types of structural fatigue. Based on the NVDB, any vehicle longer than or equal to 5.6 m is automatically clustered into the heavy vehicles group, and the number of heavy vehicles is presented as a proportion (%) of the total AADT in a particular year. In this research, the number of heavy vehicles was quantified by multiplying the AADT by the proportion of heavy vehicles to create more meaningful values; the results are presented in units of AADT-t.

Asphalt content usage quantifies the amount of asphalt used in a paved segment. The value is derived in kilograms per square meter. As a rule of thumb, every 25 $\mathrm{kg/m^2}$ is equivalent to 1 cm thickness; however, the thickness can vary as a result of different aggregate sizes, binders, and air voids contents. M&R activities also influence asphalt content usage; for example, more than one layer may need to be placed on a segment because of the fatigue level, which ultimately affects the thickness of the laid wearing courses.

Data related to traveled-way width were also extracted from the database, but they were not used as an explanatory variable. Here, the traveled-way width refers to the total width of lanes accommodating the operational needs of motor vehicles in homogeneous segments. However, it does not take into account the width of shoulders, bicycle lanes, pedestrian ways, or central reserves.

Results

The generated GIS data, described previously, were used to estimate the lifetimes of asphalt surfacing in the proposed statistical model. The analysis was performed using the statistical software R, version 3.3.2 (R Core Team 2016) using the Survival package (Therneau 2016).

Nonparametric models provide a practical outcome to project survival curves and can be used as a quality control measure before an assessment is considered in depth. As can be seen from the shapes of the survival curves (Fig. 3), stratified according to AADT classes, the duration in each stratum is negatively correlated with the number of years a surfacing is projected to last. This is similar to the results that were explained and highlighted in

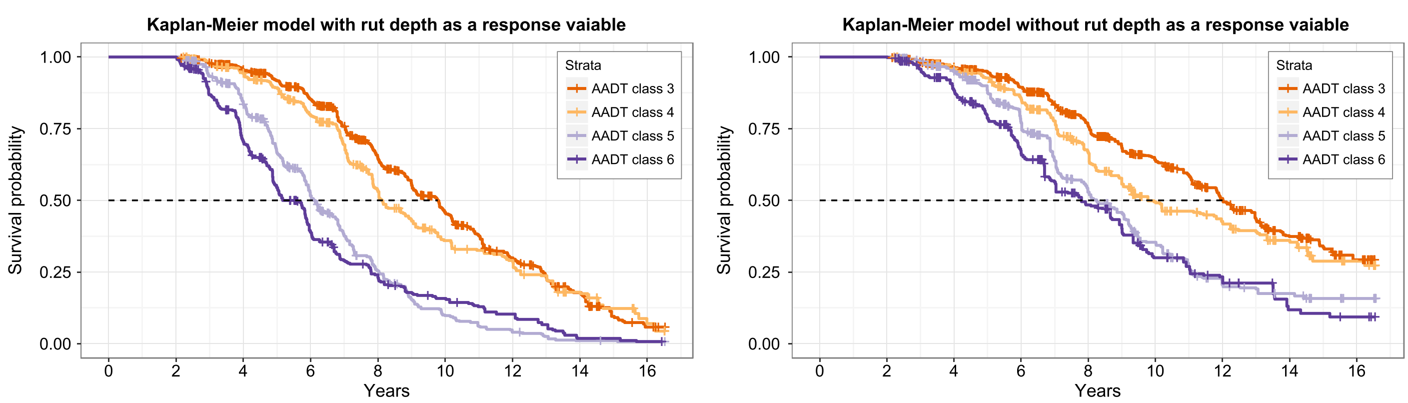

Fig. 3. Kaplan–Meier survival curve stratified according to annual average daily traffic classes.

previous studies (Gharaibeh and Darter 2003; Yang 2009; Do 2011; Svenson 2014). This means that roads exposed to a greater traffic volume are more prone to shorter lifetimes. Thus, the surfacing lifetimes are skewed to the left side of the graph for roads that are grouped in higher AADT classes. For instance, the expected median lifetimes of asphalt surfacing in AADT Class 3 were greater than those of asphalt surfacing in other AADT classes.

Fig. 3 shows the effect of including versus excluding rut measurement from the survival analysis. In the case in which rutting was not included as the condition measure, surfacing in each AADT class indicated longer median lifetimes, with survival lifetimes of almost 2 years longer.

Although the nonparametric model could provide a general lifetime estimation in each AADT class, during decades of research and developments, different surfacing technologies have been found appropriate for different AADT classes. This is due to the costs and quality assurance associated with each pavement technology that determine which surfacing types could be appropriate for a particular configuration (NPRA 2014a). In Norway for instance, wear resistibility of pavements to studded tires is an influential parameter when choosing asphalt mixes for surfacing. Such a condition results in certain surfacing types being designed for particular AADT classes to ensure condition requirements and traffic safety.

Because AADT is an influential parameter in the selection of surfacing mixture types, and to avoid the mentioned limitations of nonparametric survival analysis, it was of interest to use the semiparametric model for each AADT class, stratified by surfacing type. This approach could potentially show the survival lifetimes with higher precision.

Semiparametric Results

A mixture of continuous and discrete explanatory variables was selected to understand the differences and similarities between different parameters. Here, the continuous variables were heavy traffic volume and asphalt content usage, whereas the discrete explanatory variables were posted speed limit, bearing-capacity class, aggregate nominal maximum size, and climate zone.

Relative lifetime differences within an explanatory variable are shown by hazard ratios. A hazard ratio, i.e., the exponential of the regression coefficient, is a measure indicating the relative survival time of a covariate compared with a reference category within an explanatory variable. A hazard ratio greater than 1 corresponds to a shorter lifetime than the reference category, whereas a hazard ratio less than 1 means the opposite.

Tables 5–8 list the results obtained by the stratified Cox PH model for each AADT class. In the analysis, posted speed limit 50 km/h, bearing-capacity class T10-50, aggregate nominal maximum size 11 mm, and climate zone Sør-Trøndelag were considered to be the reference categories for the discrete explanatory variables. Bearing-capacity class was the only explanatory variable that had two covariates in AADT Class 3. However, T10-50 was the only bearing-capacity class for the remaining AADT classes.

Table 5. Cox proportional hazard model for AADT Class 3, stratified by surfacing type

Parameters	Regression coefficient	Hazard ratio	Standard error	z-value	p-value
Posted speed limit 50 km/h[a]	0	1	—	—	—
Posted speed limit 60 km/h	0.265	1.303	0.135	1.956	0.05
Posted speed limit 70 km/h	0.521	1.684	0.163	3.195	0.001
Posted speed limit 80 km/h	0.572	1.771	0.128	4.471	<0.0001
Posted speed limit 90 km/h	0.191	1.211	0.292	0.655	0.513
Bearing-capacity class T10-50b	0	1	—	—	—
Bearing-capacity class T8-50	−0.262	0.769	0.314	−0.834	0.404
Nominal maximum size 11 mm[a]	0	1	—	—	—
Nominal maximum size 16 mm	−0.224	0.799	0.107	−2.104	0.035
Climate zone Sør-Trøndelag[a]	0	1	—	—	—
Climate zone Troms	0.853	2.347	0.118	7.242	<0.0001
Climate zone Vest-Agder	−0.211	0.809	0.13	−1.625	0.104
Heavy traffic volume (AADT-t)	0.002	1.002	0.0005	5.089	<0.0001
Asphalt content usage (kg/m^2)	−0.018	0.982	0.006	−2.832	0.005

Note: Number of observations = 1,130; and number of events = 585.
[a]Refers to reference categories.

Table 6. Cox proportional hazard model for AADT Class 4, stratified by surfacing type

Parameters	Regression coefficient	Hazard ratio	Standard error	z-value	p-value
Posted speed limit 50 km/h[a]	0	1	—	—	—
Posted speed limit 60 km/h	0.329	1.390	0.165	1.991	0.046
Posted speed limit 70 km/h	0.128	1.137	0.202	0.634	0.526
Posted speed limit 80 km/h	0.217	1.242	0.171	1.270	0.204
Nominal maximum size 11 mm[a]	0	1	—	—	—
Nominal maximum size 16 mm	−0.497	0.608	0.215	−2.315	0.021
Climate zone Sør-Trøndelag[a]	0	1	—	—	—
Climate zone Troms	0.840	2.317	0.235	3.582	0.0003
Climate zone Vest-Agder	−0.960	0.383	0.173	−5.531	<0.0001
Heavy traffic volume (AADT-t)	0.001	1.001	0.0002	6.437	<0.0001
Asphalt content usage (kg/m^2)	−0.006	0.994	0.006	−0.995	0.320

Note: Number of observations = 564; and number of events = 318.
[a]Refers to reference categories.

J. Transp. Eng., Part B: Pavements, 2019, 145(3): 04019017

Table 7. Cox proportional hazard model for AADT Class 5, stratified by surfacing type

Parameters	Regression coefficient	Hazard ratio	Standard error	z-value	p-value
Posted speed limit 50 km/h[a]	0	1	—	—	—
Posted speed limit 60 km/h	−0.281	0.755	0.133	−2.108	0.035
Posted speed limit 70 km/h	−0.335	0.715	0.143	−2.350	0.019
Posted speed limit 80 km/h	−0.256	0.775	0.141	−1.807	0.071
Posted speed limit 90 km/h	−0.633	0.531	0.514	−1.229	0.219
Nominal maximum size 11 mm[a]	0	1	—	—	—
Nominal maximum size 16 mm	−1.027	0.358	0.174	−5.902	<0.0001
Climate zone Sør-Trøndelag[a]	0	1	—	—	—
Climate zone Troms	2.499	12.175	0.207	12.098	<0.0001
Climate zone Vest-Agder	−0.735	0.480	0.121	−6.089	<0.0001
Heavy traffic volume (AADT-t)	0.002	1.002	0.0002	8.644	<0.0001
Asphalt content usage (kg/m^2)	−0.001	0.999	0.007	−0.144	0.885

Note: Number of observations = 649; and number of events = 495.
[a]Refers to reference categories.

Table 8. Cox proportional hazard model for AADT Class 6, stratified by surfacing type

Parameters	Regression coefficient	Hazard ratio	Standard error	z-value	p-value
Posted speed limit 50 km/h[a]	0	1	—	—	—
Posted speed limit 60 km/h	0.363	1.438	0.186	1.949	0.051
Posted speed limit 70 km/h	0.113	1.120	0.245	0.460	0.645
Posted speed limit 80 km/h	−0.813	0.444	0.273	−2.981	0.003
Posted speed limit 90 km/h	−0.621	0.537	0.310	−2.004	0.045
Nominal maximum size 11 mm[a]	0	1	—	—	—
Nominal maximum size 16 mm	−0.782	0.458	0.157	−4.973	<0.0001
Climate zone Sør-Trøndelag[a]	0	1	—	—	—
Climate zone Troms	1.104	3.017	0.277	3.983	<0.0001
Climate zone Vest-Agder	−0.264	0.768	0.232	−1.137	0.255
Heavy traffic volume (AADT-t)	0.0003	1.0003	0.0002	1.743	0.081
Asphalt content usage (kg/m^2)	−0.004	0.996	0.006	−0.590	0.555

Note: Number of observations = 416; and number of events = 333.
[a]Refers to reference categories.

Fitted Curves

To estimate the absolute lifetimes of asphalt surfacing in a particular configuration, it was necessary to fit the survival outcomes to the intended covariate values. This could assist in gaining more meaningful outcomes from the survival estimates, which are sometimes not visible in Tables 5–8.

Fig. 4 demonstrates examples of fitted survival curves for each AADT class stratified by surfacing types. A solid stepwise curve indicates a fitted curve from the Cox PH model, representing a surfacing mixture type. Here, the selected covariate values for this mean were the same as the defined reference categories, which were posted speed limit 50 km/h, bearing-capacity class T10-50, aggregate nominal maximum size 11 mm, climate zone Sør-Trøndelag, and mean values of the continuous explanatory variables.

In addition to Fig. 4, some additional information that can help to explain better some unexpected patterns in the results is essential. This is especially helpful when the range of an AADT class becomes wider; for instance, the range of the AADT for AADT Class 6 (10,001–20,000 vehicles) was 5 times greater than that of AADT Class 4 (3,001–5,000 vehicles).

Table 9 shows the range of traffic loading for each surfacing type in its corresponding AADT class. Two variables were used in this regard when mapping the ranges: AADT and AADT-t. The variables explain which asphalt surfacing mixture type was exposed to which range of traffic loading. For instance, the AADT of 25th percentile and 75th percentile of AC in AADT Class 6 ranged between 11,500 and 16,920 vehicles, respectively. However, the AADT of SMA modified by polymers (SMA-PMB) ranged between 13,120 and 17,900 vehicles, respectively.

Discussion

The availability of Norwegian road data and utilization of GIS analyses provided a strong basis for the statistical analysis. The issue of censored data can be resolved by survival analysis, and this study used a semiparametric model to estimate lifetimes of different surfacing types in different AADT classes concerning six explanatory variables. In addition, rutting was used as the response variable to increase the validities of registered asphalt surfacing and to handle censoring when estimating lifetimes.

Stratification of data based on surfacing types in each AADT class assisted in increasing the precision of results obtained from the Cox PH model. However, this approach influenced the produced p-values. Significance levels depended strongly on the number of observations (Tables 5–8). The aim to quantify the lifetimes of different surfacing types in each AADT class in the 16-year analysis period resulted in fewer observations. This sometimes corresponded with p-values higher than 0.05 for particular covariates, even though hazard ratios indicated the expected relative likelihood of failures.

Speed Limits

Snilsberg (2008) highlighted that there is a positive correlation between vehicular speed and dust formation, and in some cases, speed

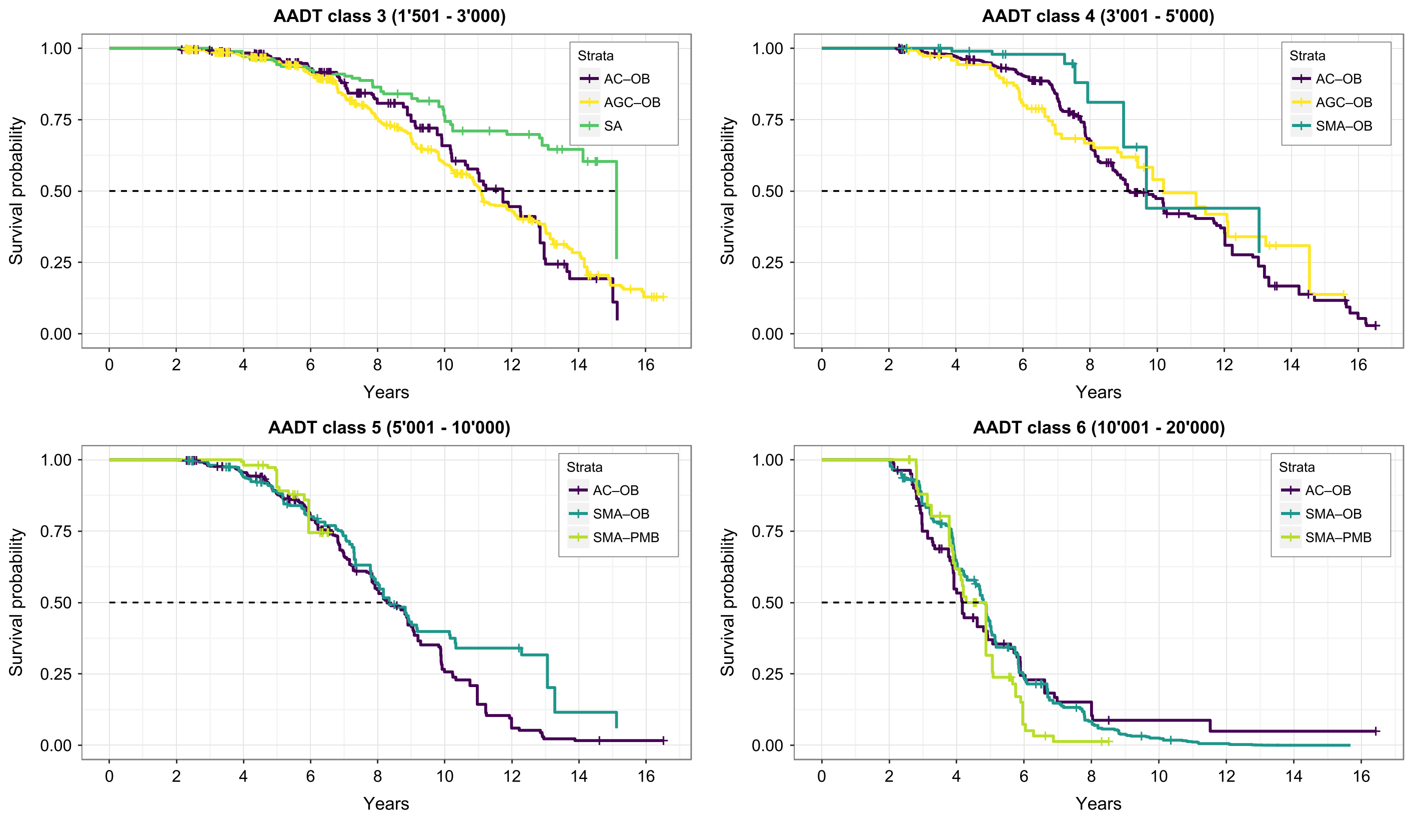

Fig. 4. Fitted survival curves from the stratified Cox proportional hazard models.

Table 9. Quantitative summary of traffic loading

Traffic class	Surfacing type	Variable	Minimum	First quantile	Median	Mean	Third quantile	Maximum	SD	No. of observations
AADT Class 3	AC-OB	AADT	1,600	2,000	2,290	2,369	2,770	3,000	396	280
		AADT-t	0	204	290	285	320	570	133	
	AGC-OB	AADT	1,510	1,722	2,000	2,061	2,300	3,000	382	782
		AADT-t	0	167	216	231	292	661	105	
	SA	AADT	1,550	1,738	2,100	2,022	2,210	3,000	277	68
		AADT-t	104	217	225	232	273	375	64	
AADT Class 4	AC-OB	AADT	3,020	3,580	4,265	4,117	4,572	5,000	575	438
		AADT-t	0	315	450	534	738	1,400	303	
	AGC-OB	AADT	3,040	3,170	3,450	3,640	4,050	4,900	544	85
		AADT-t	0	284	380	402	514	893	187	
	SMA-OB	AADT	3,080	3,600	4,500	4,261	4,800	5,000	630	41
		AADT-t	0	461	496	719	1,305	1,398	439	
AADT Class 5	AC-OB	AADT	5,010	5,400	6,825	6,954	8,192	10,000	1,520	384
		AADT-t	261	540	846	852	1,103	1,530	335	
	SMA-OB	AADT	5,020	6,608	8,500	7,998	9,375	10,000	1,631	47
		AADT-t	261	656	1,022	943	1,208	1,474	314	
	SMA-PMB	AADT	5,100	650	0 8030	7,760	8,700	9,690	1,409	87
		AADT-t	565	934	1,066	1,051	1,169	1,381	199	
AADT Class 6	AC-OB	AADT	10,100	11,500	14,900	14,480	16,920	19,000	2,896	87
		AADT-t	405	709	989	1,234	1,746	2,418	606	
	SMA-OB	AADT	10,020	12,650	15,060	15,180	18,100	20,000	2,983	237
		AADT-t	625	1,200	1,593	1,479	1,756	2,352	426	
	SMA-PMB	AADT	10,020	13,120	16,010	15,360	17,900	19,950	2,947	92
		AADT-t	660	1,453	1,870	1,825	2,231	2,703	498	

Note: SD = standard deviation.

may cause rut propagation. Roads exposed to higher traffic speeds are often prone to more wear because of the increase in kinetic energy between the tires and the surface layer. This could also be interpreted as a shortening of the lifetimes of asphalt surfacing in heavily trafficked roads. This was validated by the values in Tables 5–8. Pavement types in AADT Classes 3 and 4 were mainly ordinary two-lane roads, which have quite similar traveled-way widths concerning the baseline category of 50 km/h. The range of traveled-way widths for AADT Class 3 was from 5.8 to 6.4 m, whereas the range was from 6.2 to 7.1 m for AADT Class 4, i.e., these ranges were based on the 25th and 75th percentiles.

In contrast, this analogy was not relevant for AADT Classes 5 and 6. This alteration in the results was due to parameters other than vehicular speed. As the number of vehicles passing through an alignment starts to increase, the geometry of roads is designed to reduce accident risk. This results in design solutions that provide wider roads (and sometimes results in more than one lane per direction), better view angles, and higher posted speed limits.

Roads in AADT Class 5 had lower hazard ratios as the traffic speed increased. The underlying reason could be the traveled-way width and traffic loading. Most of the roads in this AADT class were ordinary two-lane roads, but the traveled-way width for the baseline category was narrower than that for the other categories. The baseline category, designed for an allowed speed of 50 km/h, had traveled-way widths in the range 6.1–6.7 m, whereas the others had slightly wider traveled ways (6.4–7.2 m). In addition, the baseline category had been subjected to a slightly higher share of vehicles (AADT) than their counterparts, except for 70-km/h segments that showed higher heavy traffic loading.

Likewise, the unexpected patterns in hazard ratios for roads in AADT Class 6 originated from the geometric differences in which homogeneous segments were designed with different posted speed limits. Homogeneous segments for which the posted speed limits were 50, 60, and 70 km/h were mainly ordinary 2-lane roads. However, roads with posted speed limits of 60 and 70 km/h were subjected to a higher range of heavy traffic loading than the reference category. The median value of the AADT-t for the baseline category was 920 heavy vehicles, whereas it was 1,212 and 1,646 heavy vehicles for homogeneous segments with posted speed limits of 60 and 70 km/h, respectively.

Despite having higher traffic loading than the baseline category in AADT Class 6, segments with posted speed limits of 80 and 90 km/h had lower hazard ratios. This was mostly because roads with these speed limits were wider than roads with lower speed limits. In some segments, the increase in the width resulted in there being more than one lane per direction, such that road types 2 + 1 or four-lane roads (two lanes in each direction) were among the dominant road types in roads on which the posted speed limits were 80 and 90 km/h.

In addition to road width and traffic loading, other parameters exist that were not attainable from the data. One parameter, and by far the most influential, is the construction or rehabilitation history. Newly rehabilitated roads are most frequently expected to last longer than roads that have not been rehabilitated. This is often because of having better structural compositions and fulfilling higher construction requirements. The existence of such parameters could have assisted a better interpretation of the patterns in some of the results.

Bearing-Capacity Class

The bearing-capacity class is a measure that indicates the maximum axle load allowed to prevent destruction of structures while ensuring traffic safety and road accessibility and availability. The inclusion of the administrative bearing-capacity classes as the explanatory variable was possible only in AADT Class 3 because T10-50 was the only bearing-capacity class included in the other AADT classes. By assessing the statistical outcomes, no evidence of statistical significance can be seen in Table 5, i.e., the p-value was above 5%. However, the results of the hazard ratio were aligned with those of a previous study conducted in Sweden (Svenson 2014), such that roads with a lower permitted axle load might last longer because they have lower fatigue loading.

Aggregate Nominal Maximum Size

After AADT-t, the nominal maximum size was, by far, the explanatory variable that indicated the strongest evidence of an effect on the asphalt surfacing survival time. It has also been agreed in Norway that the existence of a larger aggregate size may increase the expected lifetimes for surfacing because of a higher wear resistance (Snilsberg 2008; Sabba et al. 2009); however, the mechanical properties of aggregates also play a key role in this regard.

The results show the expected evidence for the importance of nominal maximum size on the lifetimes of surfacing. Asphalt surfacing with a nominal maximum size of 16 mm had lower hazard ratios than those with a nominal maximum size of 11 mm. The hazard ratios ranged from 0.799 to 0.358, but the greatest effect on the increased survival time occurred with an AADT of more than 5,000 vehicles. This means that asphalt surfacing with a nominal maximum size of 16 mm had a lower failure risk, approximately 64% in AADT Class 5 and 54% in AADT Class 6.

Climate Zone

In any guidelines for pavement and structure design, climate conditions have been considered to be one of the key parameters influencing the durability of pavements. Norway is a country with various microclimates. In part of a published report by the NPRA (Evensen 2011), climate conditions were zoned to address the variability of microclimates along the road networks. The method allocated a particular climate to each zone, defined by municipality borderlines. In total, 15 unique climate conditions were suggested for Norway. Despite the zoning method suggested in the report (Evensen 2011), because too few sample data existed in some municipalities, this study considered zoning based on the borderlines of each county.

Despite the zoning approach, results in all AADT classes showed that asphalt surfacing located in the northern part of Norway, i.e., Troms, had a higher hazard ratio, i.e., lower expected lifetimes, than the reference category, i.e., Sør-Trøndelag. In contrast, asphalt surfacing in Vest-Agder (southern Norway) had a lower hazard ratio than the baseline category. Based on statements of the NPRA (2014c), studded tires could be used for a longer duration in cold climates, such as Troms, than in the other two counties. The permitted period for winter tire or snow chain use is from October 16 to April 30 in Troms, which is almost 1 month longer than in the other two counties.

An ambiguous outcome was found for the effect of climate in AADT Class 5. The lifetime in Troms was shorter by a factor of 12 than the baseline category. Such a significant difference could have various sources. The observed layout of traffic lanes makes it clear that the traveled ways were narrower in Troms than in the middle and the south of Norway. Narrower roads, particularly lanes, result in less freedom for drivers. This might cause restrictions in lane keeping and more accurate steering behavior, which could subsequently result in a narrower and deeper rut depth (McGarvey 2017). This could occur as the repetition of loading becomes limited to certain strips in the wheel path, resulting in faster and deeper overcompaction than in a wider traffic lane.

Continuous Explanatory Variables

Two continuous variables were studied: annual average daily traffic of heavy vehicles (AADT-t) and asphalt content usage.

Heavy traffic loading significantly decreased the survival time of the surfacing for each additional AADT-t (e.g., from 101 to 102 heavy vehicles). The observed hazard ratios were significant for all AADT classes. The hazard ratios were approximately 1.002 for AADT Classes 3 and 5, approximately 1.001 for AADT Class 4, and approximately 1.0003 for AADT Class 6. This implies that with an increase of 1 in the number of heavy vehicles, i.e., vehicles longer than or equal to 5.6 m, in a homogeneous segment, the risk of failure increased by 0.2%, 0.1%, and 0.03%, respectively; i.e., a 0.2% increase in risk for AADT Classes 3 and 5, a 0.1% increase for AADT Class 4, and a 0.03% increase for AADT Class 6.

Conversely, an increase in the thickness of a paved wearing course had an opposite expected effect on the lifetimes. The corresponding hazard ratio for AADT Class 3, the only AADT class with a p-value less than 0.05, was 0.982 for each 1 $\mathrm{kg/m^2}$ increase. This means that an increase in the density of the surfacing of 1 $\mathrm{kg/m^2}$ (ca. 0.4 mm), increased the expected lifetimes by 1.8% for AADT Class 3. In other words, the risk of failure for the surfacing was expected to decrease by 1.8% with one additional density unit.

Although the hazard ratios for both continuous variables look negligible for each additional unit, the results were presented on exponential scales. To quantify the hazard ratio for the risk of failure for a continuous variable when it is increased by units other than 1, the hazard ratio needs to be exponentiated to adjust the hazard ratio respectively. For instance, if the asphalt content use in AADT Class 3 increases by 10 $\mathrm{kg/m^2}$ instead of 1 $\mathrm{kg/m^2}$, then the life expectancy of the asphalt surfacing material is expected to increase by 16.6% rather than 1.8%, i.e., $1 - (0.982)^{10}$.

Fitted Survival Curves

In general, it is possible to generate various combinations of fitted survival curves to generate absolute values of lifetimes. This discussion is structured based on the obtained results in Fig. 4 with the specified covariate values. In addition, Table 10 compares the fitted results with the expected lifetime of asphalt surfacing projected by the NPRA (NPRA 2014a).

AGCs are often paved on roads with an AADT below 5,000 vehicles, and they differ from ACs mainly as a result of the binder grade: AGC surfacing uses softer binders than do ACs. Use of softer binder frequently results in AGCs having shorter lifetimes than ACs (NPRA 2014a). This condition was validated by comparing the survival curves of AGCs with those of ACs in AADT Class 3. However, the condition did not hold in AADT Class 4. The median lifetimes of AGCs were approximately 1 year longer than those of ACs. A lower share of traffic loading typically increases the probability of longer lifetimes. AGCs were exposed to lower traffic loading (both lower AADT and lower AADT-t) than ACs (Table 9).

Despite the effect of the traffic volume on the longevity of pavements, the longevity of SAs was not fully explainable by the traffic volume. Based on the fitted curves in AADT Class 3, SAs had longer expected lifetimes than ACs and AGCs. This was surprising because SAs are typically cheaper surfacing solutions and have shorter nominal lifetimes than ACs and AGCs (NPRA 2014a) (Table 10). This study was unable to address the underlying factors that could explain the longer lifetimes of SAs than AGCs. However, in the case of ACs, the reason for shorter lifetimes can be interpreted according to the traffic volume: ACs were subjected to higher traffic volumes and had a higher share of heavy vehicles than SAs (Table 9).

If historical data cover a short period of assessment, so that very few objects failed during an analysis period, semiparametric models may not ensure appropriate estimation, because the hazard in semiparametric models is quantified until the last observed failure. Such a pattern can be observed in the case of SMA-PMB in AADT Class 5. Because of the few failures for SMAs containing PMB in this traffic class, 75% of observations were in-service roads. Thus, it was not possible to find a median lifetime for SMA-PMB with the semiparametric model.

SMAs were successfully developed for the first time in Germany (Bellin 1998). This success was due to the unique properties of SMAs that make them resistant to wear. In Norway, SMAs are used mostly for high-traffic roads (an AADT greater than 3,000 vehicles) and are expected to last longer than ACs. Typically, the nominal surfacing lifetime of SMAs is expected to be about 1 year longer than the nominal surfacing lifetime of ACs (NPRA 2014a). The median lifetimes of the fitted curves in Fig. 4 show that SMA surfacing with ordinary binder performed slightly better (i.e., had relative longer lifetimes) than AC surfacing. The median lifetimes for SMAs in AADT Classes 4, 5, and 6 were 9.19, 8.34, and 4.79 years, respectively; however, the median lifetimes for ACs in the same AADT Classes were 9.68, 8.28, and 4.17 years, respectively. From the summary of traffic data in Table 9, the reasons for these slight differences are self-explanatory.

Use of PMBs was found to be an alternative to using ordinary binders because of their properties that enhance resistance to the wear caused by studded tires. This finding was also proven in laboratory tests in Norway (Sabba et al. 2009). Despite the test results obtained, the survival lifetimes were somewhat shorter than those of OBs in AADT Class 6. This means that the median projected lifetime of SMA-PMBs was shorter than that of SMA with an OB.

This disadvantage of SMAs containing modified binders in terms of duration was similar to that in the cases discussed earlier. The traffic loading in Table 9 indicates that SMA containing modified binders was exposed to a greater number of vehicles (AADT) and heavy vehicles (AADT-t) than the other two surfacing types.

However, the unusually long or short survival times might be due to causes other than traffic loading that could not be identified from these data, such as the quality of the aggregates used in the mixtures, the grade of binders, or the quality of surfacing.

Table 10. Expected lifetimes of asphalt surfacing in Norway (years)

	AADT class			
Asphalt surfacing	3	4	5	6
SMA	—	13	10	7
AC	15	12	9	6
AGC	14	11	—	—
SA	12	—	—	—

Limitation and Future Work

Although the influence of M&R activities on the longevity of surfacing is interesting, we did not address this topic in this study, but left it for future research. The analysis in this study was confined to the lifetime estimation of asphalt surfacing in the Norwegian context, and it was hypothesized that the applied M&R activates were aligned with the NPRA's maintenance standard and should result in long-lasting asphalt surfacing. However, a project conducted in Norway (Telle 2015) highlighted that the low quality of finished work rather than the job mixes was one of the reasons for premature failures occurring in Norwegian roads. Based on the report, causes of premature failures could be the lack of a tack coat, nonhomogeneous asphalt, open joints, and long-distance transport of mixtures. In addition, types of overlaying preservation techniques and their relative effects were not assessed in this study because they were undocumented in the collected data.

Because of the limitations of the available data, this study could not use AADT per lane. Instead, it used AADT for the entire cross section of a paved road over a homogeneous segment. Using AADT per road cross section has the shortcoming that is not possible to precisely interpret the causality of traffic loading in surfacing. Traffic loading per lane may have a more rational causal relationship with surfacing lifetimes than AADT per road cross section.

In future research, it would be worthwhile to use other types of surveying data in addition to the rut measurement data, such as longitudinal unevenness and surface texture, to increase the credibility of the research results and evaluating their effects on the entire AADT classes. Although rut measurements could be used as an indication of the quality of an in-service pavement, a road might undergo maintenance activity for reasons other than rutting, such as fatigue crack, polishing, raveling, and depression. Hence, the inclusion of other survey data as response variables might assist in improving the validation of the surfacing lifetimes.

The fitting of the estimated results of survival analysis can be based on nondistributional and distributional methods. Although the survival function is a smooth curve in theory, i.e., it is plotted from time zero to infinity, the use of empirical nondistributional methods in this study resulted in the survival curves being plotted in stepwise curves. This is because, by its nature, the model is too tightly tied to observed data (Yang et al. 2013). In future, it will be of interest to use distributional methods, such as the Weibull, loglogistic, and lognormal functions, to find smooth and optimal fits from the semiparametric estimates.

Conclusion

By breaking down the real data into separate AADT classes and then executing Cox PH models, stratified by asphalt surfacing types, more meaningful results were obtained in this study than in previous research. The semiparametric model resolved the shortcomings in the deterministic models by making no assumption regarding the distribution of stratum-specific baseline hazard functions while evaluating different covariates simultaneously.

The initial results showed that the time of interventions, based on the median lifetime of asphalt surfacing, were backlogged for approximately 2 years for each AADT class when rutting was considered as the response variable.

The results of the stratified Cox PH models showed that aggregate nominal maximum size and heavy traffic volume were the only covariates that were constantly significant in the studied AADT classes. The surfacing survival time increased when a larger aggregate size, i.e., 16 mm instead of 11 mm, was selected; an increase in nominal maximum size from 11 to 16 mm increased the lifetimes by 20.1%–64.2%. However, an increase of 1 unit of heavy vehicles shortened the expected lifetimes of asphalt surfacing by 0.03%–0.2%.

The different climate zones of the road networks had differences in the longevity of surfacing: the surfacing materials in the northern part of Norway had shorter expected lifetimes than those located in central and southern Norway. The findings were analyzed and expected to be caused by the longer duration of using studded tires and narrower traveled-road width. In AADT Class 3, an increase in the density of asphalt surfacing of 1 kg/m^2 significantly increased the longevity of the surfacing by 1.8%. Similarly, an increase in the posted speed limit significantly reduced the survival time of the surfacing in AADT Classes 3 and 4 (approximately 30%–40%). This behavior was found to be due to the increase in asphalt abrasion on roads where the speed limit was higher, as was highlighted in prior studies in Norway.

Although the traveled-way width was not inserted as an explanatory variable in the models, it was shown that the traveled-way widths could influence the longevity of the surfacing, and it was able to explain some of the behaviors in the obtained results.

This study also helped show the extent of the absolute lifetimes of asphalt surfacing in the Norwegian context. The results of the survival curves fitted to certain baseline categories showed that some surfacing types had surprisingly longer or shorter median lifetimes than the surfacing lifetimes estimated by the NPRA. The majority of the contradictions in the estimated results were explainable. In the cases in which the estimated lifetimes were longer for a particular asphalt surfacing, the reason was found to be lower traffic loading during the time they were in service. The opposite condition also held. However, further research is needed to enhance the understanding of asphalt surfacing in Norway, such as the inclusion of response variables other than rutting, better climate zoning of road networks, and so on.

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