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Municipal street maintenance challenges and management practices in Sweden

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The municipal street network acts as a multifunctional asset by providing people, vehicles and public services with a well-functioning infrastructure. To keep it in good condition, optimal maintenance measures are required which would result in an efficient use of taxpayers' money. This paper investigates the street network deterioration processes and the management practices that the municipal administrations have applied in Sweden. The study is based on a survey with Swedish municipalities using questionnaires and complementary interviews. The answers provide insight into a wide range of common pavement distresses and deterioration factors, along with pavement management practices. The study identifies that potholes, surface unevenness and alligator cracking are the most cited challenges, while pavement ageing, heavy traffic and patches are the most noted causes. Similarly, the cold climate and population density are influential factors in pavement deterioration. Allocation of the maintenance and rehabilitation and reconstruction budget is higher in the northern part of the country as well as in densely populated municipalities. Condition data collection and use of commercial Pavement Management Systems (PMS) are limited. Addressing the challenges effectively may be possible through the enhancement of the budget, feasible/clear guidelines from municipal councils/politicians, and reducing the gap between street network administrations and utility service providers.

KEYWORDS

pavement management systems, road maintenance, municipalities, budget allocation, questionnaire, pavement deterioration, cold climate

1 Introduction

Streets or urban roads are an essential asset in any community due to their multifunctioning nature, as they provide not only movement to traffic and people but also utility services. Streets in good condition are therefore vital to the enhancement of socioeconomic value and urban liveability (International Road Federation, 2007). Demographic and environmental changes are the main factors that constantly put unanticipated pressure on street pavements. Consequently, timely maintenance is imperative to keep the serviceability of the street network at the predefined performance level (PIARC, 2019).

It is a constant challenge to maintain street pavements in good condition within the limited maintenance budget, particularly for small municipalities. The shortfall in funding for maintenance is a common issue in Europe (European Union Road Federation, 2018), resulting in delayed maintenance and rehabilitation (M&R) activities. Delaying maintenance treatment can compromise the condition of the pavement network significantly (Chang et al., 2018), with a remarkable increase in the long-term pavement maintenance cost as a consequence (Tavakoli et al., 1992), while road users and environmental costs are additional burdens. Furthermore, limited funding restricts the wide range of treatment measures (Hafez et al., 2019). Relatively expensive construction, operations and maintenance of cold region pavements highlight the scarcity of budget and resources among pavement administrations (Doré and Zubeck, 2009).

For the pavement maintenance staff, ensuring sustainable maintenance solutions in pavement management provides further complications (NAS, 2011). Ramani et al. (2009) noted that only 30% of the US state transportation agencies address the sustainability concept (economic, social and environmental) in their pavement maintenance decision-making. However, this requires up-to-date pavement condition data and prediction models to evaluate the impact of maintenance strategies on the socio-economic and environmental factors in achieving sustainable pavement management (Flintsch and Bryce, 2014).

Keeping streets in good condition may be achieved through implementing an effective pavement management strategy and better cooperation among stakeholders. Pavement Management System (PMS) is a useful tool in the decision process for prioritizing maintenance strategies to reach optimal use of the maintenance budget by predicting the future pavement condition (Tavakoli et al., 1992; Shahin, 2005; Uddin et al., 2013). In light of this, PMS has been in place at the network and project level for several decades (Haas et al., 2015) to maintain the pavement network systematically and strategically intact (Loprencipe and Pantuso, 2017; Saha et al., 2017). It has been developed by many transport agencies (Pérez-Acebo et al., 2018) for various network levels, e.g., state roads (Flintsch and McGhee, 2009; Zimmerman, 2017; Peshkin and Duncan, 2021), local roads and municipal streets (Douglas, 2011; Wolters et al., 2011; He et al., 2017).

The use of pavement data in a PMS is common in selecting treatment alternatives among US state transportation agencies, although the use of environmental sustainability data is lacking in it (Zimmerman, 2017). In another study, it was found that traffic volume, maintenance history and structural data are important factors in building PMS among Colorado local agencies (Hafez et al., 2019). In Iowa State, US, collection of pavement distress data is lacking in 70% (of 74 respondents) of the local agencies, and therefore subjective maintenance practice prevails (Abdelaty et al., 2017).

The condition of the pavement network can be assessed through manual (visual survey/windshield) and sensor-based surveys i.e., automated and semi-automated (Sholevar et al., 2022). The cost of the manual method is low compared to the sensor methods but is a subjective approach (Staniek, 2021). Sensor methods require different data collection devices, namely,: cameras, different road sensor devices, friction, and deflectometer (Coenen and Golroo, 2017). Survey vehicles equipped with multi-devices can be used to measure a wide range of pavement distresses and other pavement performance parameters (Coenen and Golroo, 2017; Benmhahe and Chentoufi, 2021). Sensor-based data collection is comparatively useful in data-driven pavement management, provided that effective condition data quality management is in place throughout the survey (Underwood et al., 2011).

The pavement maintenance management practices at the local level (i.e., urban roads/streets) in the UK, maintenance funding, safety concern and classification of roads are the most decisive factors respectively, while average daily traffic was the least decisive factor in prioritizing the pavement maintenance decisions (Alfar, 2016). A study revealed that the local maintenance authority in England and Wales has a maintenance backlog of nearly £12.64 billion, which reflects the poor condition of local roads and lack of funding (Asphalt Industry Alliance, 2022). Further, it was reported that pavement ageing and pothole repair are the main challenges that the local authorities are facing since the average age of pavements is 70 years and total spending on pothole repair reached £1 billion in 2022 (Asphalt Industry Alliance, 2022).

The classification of road networks is important in managing traffic and budget utilization in the Toronto province (City of Toronto, 2017). A survey revealed that rutting and fatigue crackings are the most commonly collected distresses among Canadian cities and municipalities, followed by ravelling, transverse cracking and edge cracking; however, the frequency of collecting pavement distress data is subject to the availability of funding (Farashah and Tighe, 2014). According to a study, almost 40% of municipal roads are either at a fair or significant deterioration stage among the Canadian municipalities that responded (CIRC team, 2019), which could be the reason that pavement rehabilitation and reconstruction are more predominant than pavement preservation among the municipalities in Alberta (Newstead et al., 2018). Moreover, it was reported that there is significant variation in the implementation of infrastructure management plans between small and large municipalities (CIRC Team, 2019). Another study revealed that the engineering judgement approach prevailed among Canadian municipalities, particularly in small municipalities (Hajek et al., 2004).

Municipalities in Sweden are politically administrated organisations that maintain their street networks through municipal tax (Alm et al., 2021). However, the estimated backlog of municipal streets amounted to 12 billion Swedish crowns (SEK), while 8% of the municipal road network needs immediate rehabilitation or reconstruction (Ekdahl et al., 2016). Furthermore, only 50% of pavements had over 7 years of remaining service life (Ekdahl et al., 2016). The choice of pavement condition data assessment varies among municipalities due to street network size and the extent of the maintenance budget (Wilén, 2016).

To highlight the challenges of pavement management at the municipality level in Sweden, a questionnaire was formulated and disseminated to all municipalities across the country. The main purpose of the survey was to get first-hand information about the present practices of maintaining the streets at the municipal level. Furthermore, some of the respondents were selected for in-depth interviews to discuss pavement maintenance approaches in their respective municipalities. This study presents the results of the questionnaire regarding pavement distresses and their causes, along with the municipal transport street/road administration's approach to meeting these management challenges. The aim of the study is to provide better information on the status of street maintenance among municipalities in Sweden, which can then be used as a foundation for improving pavement management practices in municipalities.

2 Municipal pavements network management

2.1 Pavement structural design and deterioration

Flexible pavements are generally designed for 20 years and are based on a multi-layered elastic approach to withstand both traffic and environmental loads. In the design process it is usually assumed that pavement materials are horizontally infinite while the subgrade is vertically infinite and traffic is represented as equivalent single axel loads (ESALs) (Huang, 2004; Garber and Hoel, 2009; Zhang, Mills-Beale, and You, 2011; Mallick and El-Korchi, 2013). Typically, flexible pavements are supposed to diminish the induced stresses (compression, tensile and thermal) due to traffic loading and environmental changes to prevent the occurrence of pavement distress. The core of pavement design is to withstand traffic loading or environmentally induced excessive deformations (Sun, 2016), which can be achieved by selecting suitable materials for pavement structures in the design, construction and maintenance stages. To meet the pavement design requirement, the design approach aims to control fatigue cracking and rutting by addressing the tensile stress at the underside of the bound layer (asphalt) and the vertical, bottom-up compressive stress at the top of the subgrade (White et al., 2002; Sun, 2016). The thickness of the pavement varies in order to meet the expected functionality and serviceability performance during its designed life period.

Municipality street networks generally have a relatively low traffic volume compared to highways, which may vary from one street to another due to the functionality of the streets. The speed limit on asphalt-paved streets in municipalities usually varies from 30 km/h to 70 km/h, which is relatively low compared to highways. Similarly, streets do not usually include side ditches but cycle paths, parking places, street light poles, traffic sign poles, green strips, drainage inlets and utility inlets are commonly adjacent to the pavement structure. This implies the need for a different strategy for the construction and maintenance of street pavements.

Generally, the performance of flexible pavements is influenced by several factors: traffic volume, axle loads and their configurations, environmental and climate conditions, construction and maintenance strategies (both summer and winter), drainage, and functionality of the road/street or a combination thereof (Mallick and El-Korchi, 2013; Sun, 2016). The environment and serviceability level of the pavement govern the influence of the aforementioned factors, e.g., the type and severity of distress may be different compared to urban roads or highways (Lavin, 2003). Consequently, understanding the occurrence of pavement distresses in an urban context is complex due to uneven traffic conditions and the diverse functionality of pavements (Sadeghi et al., 2017).

Asphalt pavement distresses/defects can be categorized into four groups: cracks, deformations (including surface abrasion and unevenness), surface defects and edge defects (Fwa, 2006). Pavement cracks are common defects and are herein limited to longitudinal (incl. alligator/fatigue cracking), transversal and frost heave/thaw cracking. The mechanisms involved in the occurrence of these cracks are mainly due to fatigue-induced stresses and temperature, along with construction joints/laps. Longitudinal cracks occur in the direction of the pavement, which may be induced either due to traffic loading or non-traffic loading (Lavin, 2003). Longitudinal cracks along the wheel paths are load-driven (Lavin, 2003), which if left unattended will result in alligator cracking and eventually potholes (Pearson, 2012). However, non-load-induced longitudinal cracks occur outside the loading area or wheel paths due to several reasons, e.g., differential frost heaving (Doré and Zubeck, 2009; Churilin et al., 2018), construction joints/laps etc (Lavin, 2003). Alligator cracking in flexible pavement, i.e., bottom-up cracking due to repeated application of traffic loading, may prematurely occur in cold regions due to poor pavement drainage as a result of frost thaw (FT) cycles (Doré and Zubeck, 2009). Large fluctuations in the pavement temperature may even result in longitudinal and transverse cracks (Huang, 2004). Transverse cracks develop perpendicular to the travel direction, mainly due to low temperature, an abrupt change in the pavement temperature or aged binder (Lavin, 2003; Mallick and El-Korchi, 2013; Sun, 2016). The initiation of low-temperature cracks in pavements generally takes place in the asphalt-bound layers, but it may also begin in the underlying frozen layers or subgrade due to the development of ice lenses (Doré and Zubeck, 2009). Furthermore, tree roots in the vicinity of the street may also produce cracks in the pavements.

Pavement deformation commonly includes rutting, corrugation, shoving and frost heaving. Rutting distress is a permanent longitudinal depression of asphalt pavements in the wheel paths as a consequence of repeated traffic loading (Doré and Zubeck, 2009; Erlingsson, 2012; Alaswadko and Hassan, 2018). It may occur due to one or more reasons in all layers, both asphalt-bound layers and unbound layers, including subgrade (Huang, 2004; Pearson, 2012). Rutting in the unbound layers or subgrade may occur as a result of the thaw period that significantly reduces the bearing capacity due to the presence of the excess amount of melted water in the unbound layers of the pavement (Doré and Zubeck, 2009; Salour and Erlingsson, 2013). Pavement deformation in the form of surface wear, i.e., rutting, is common due to the usage of studded tyres in cold regions (Lundberg et al., 2019). However, wear on the surface course is more prominent on free-flow roads compared to residential streets (Arrojo, 2000; Snilsberg et al., 2016). Similarly, in the urban environment asphalt pavement wears down commonly at road intersections and bus stops, due to braking, slow movement and acceleration of vehicles (Transit, 2000; Hajj et al., 2007; Al-Qadi et al., 2009; Ali et al., 2009; Li et al., 2013). Moreover, both raised and unraised pedestrian crossings are observed as places that are vulnerable to surface wear in an urban environment. The surface resistance of asphalt pavement to abrasion can be improved at the design stage by opting for a higher aggregate size of coarse aggregate in the dense-graded or stone-rich mastic asphalt concrete, which on the other hand might compromise the noise level (Snilsberg et al., 2016).

Corrugation and shoving distress are plastic deformations of wearing course that appear in the shape of ripples (perpendicular to the pavement) and horizontal displacement (in the direction of pavement), due to the combined effect of acceleration or deceleration of vehicles and inadequate asphalt mix, poor bonding between layers or insufficient stability (Lavin, 2003; Fwa, 2006; Mallick and El-Korchi, 2013). Similarly, in cold regions, the uneven upward expansion or heaving of pavement structure due to the formation of ice lenses in the pavement results in pavement deformations (Doré and Zubeck, 2009; Pearson, 2012). Pavement surface unevenness occurs both in longitudinal and transverse directions due to corrugation, shoving and frost heaving (Wågberg, 2003).

Flexible pavements can incur surface defects, which are herein referred to as bleeding, ravelling, potholes and patches that can significantly affect the serviceability and skid resistance of the pavement (Fwa, 2006). Bleeding is a construction defect which refers to the appearance of asphalt binder on the pavement surface that results in a soft pavement surface due to the presence of an excessive amount of bitumen in the asphalt mixture (Garber and Hoel, 2009). Repeated traffic loading or over-compaction of asphalt, typically in hot weather conditions, results in the upward movement of asphalt-rich binder to the surface (Lavin, 2003; Fwa, 2006; Pearson, 2012). On the other hand, ravelling is common in cold and wet conditions where it refers to the progressive disintegration of both binder and aggregates from pavement wearing course due to poor compaction, inadequate asphalt binder or pavement ageing (Lavin, 2003; Fwa, 2006).

A pothole is a formation of localized depression or cavities in the pavement surface that may be developed in both wet and dry conditions (Wilson and Romine, 2001; Doré and Zubeck, 2009). Potholes may be formed due to poor base support, the presence of moisture in the pavement, FT cycles and repetitive traffic loading, or a combination of these factors (Jassal, 1998; Wilson and Romine, 2001). The seepage of moisture into the pavement is due to the presence of low-temperature or alligator cracking (Han et al., 2019) which is either left unaddressed or is addressed but not early enough (Marasteanu, 2018). The occurrence of potholes is more common in the case of fluctuating weather conditions or FT cycles—FT cycles was cited as the major cause of potholes in Canadian provinces, followed by traffic load, poor drainage and pavement age (Biswas et al., 2018). Further factors which contribute to pothole formations include type and thickness of asphalt, oxidation, rate and amount of precipitation and winter maintenance strategy, together with the method and material used for pothole repair (Biswas et al., 2018).

Patches result from repairing potholes, low-scale improvements of pavement condition and regular cuts for utility networks. Regular cuts and backfilling for utility networks on street pavements result in premature pavement deterioration (Yapp et al., 2001; Wilde et al., 2018). In cold regions, patches may be vulnerable to frost heaving and FT cycles due to the use of non-homogenous material relative to the surrounding pavement or poorly backfilled material around stormwater inlets or other water supply installations (Wågberg, 2003). The impact of potholes, regular utility cuts and patching not only deteriorate the pavement but also has a huge impact on traffic delays, user cost and comfort, safety, air quality, local businesses, and public perception of the effectiveness of municipal maintenance departments (Arudi et al., 2000; Wilde et al., 2018).

Flexible pavements are also subject to edge defects in the form of edge deformation as a result of insufficient pavement width, poor edge/shoulder support and pavement resurfacing (Fwa, 2006). A weak unbound layer due to frost action may also result in edge deformation (Ahmed, 2017).

Ageing is a well-recognized distress in asphalt pavements (Huang and Di Benedetto, 2015) which has been reported in England and Wales (Asphalt Industry Alliance, 2022), the US and Canada (Kim, 2014) due to a lack of funding and resources. Asphalt ageing has negative effects on pavement performance due to the degradation of bitumen in asphalt over time (Chai et al., 2014; Jing et al., 2021). It is influenced by several mechanisms; however, oxidation is the most significant mechanism that affects the durability of the bitumen in asphalt (O'Nions and Preston, 2015; Speight, 2016). In addition to this, the characteristics of asphalt, aggregates and particle size distribution, as well as the void ratio of the asphalt mix, also affect asphalt ageing (Speight, 2016). Asphalt undergoes both short-term and long-term oxidations that result in the hardening of asphalt over time (Speight, 2016; Sirin et al., 2018). Short-term or first-phase oxidation takes place during the production, storage, transportation and laying of asphalt, while long-term or second-phase oxidation takes place during the in-service life of asphalt (Speight, 2016; Sirin et al., 2018). However, several aspects of ageing are not sufficiently well understood (Doré and Zubeck, 2009; Underwood, 2015). Initial significant ageing happens in the first phase and during the first few months of the second phase. This later gradually slows down but keeps continuing until the end of its design life (Doré and Zubeck, 2009; O'Nions and Preston, 2015; Sirin et al., 2018). Oxidation of the asphalt has a direct relation to the exposing temperature, period of exposure and bitumen film thickness in asphalt (O'Nions and Preston, 2015). Aged asphalt pavements are more vulnerable to cracks, moisture-related damage, pothole formation and surface wear (Doré and Zubeck, 2009; Roque et al., 2015; Underwood, 2015).

2.2 Swedish municipality perspective

Sweden is located in Northern Europe with a population of approx. 10.4 million and has a total of 290 municipalities (SCB, 2020). There are approximately 623 thousand km of roads in the country. Municipalities own approx. 7% of these (mainly streets) while the Swedish Transport Administration owns approx 16% of roads (highways) (SKR, 2021). Due to safety in severe winter conditions, winter tyres (studded and specially designed winter tyres) are mandatory (December to March) but the use of studded tyres is relatively higher than that of other winter tyres in the country. Overall, the estimated use of studded tyres in Sweden is 55%; however, in the northern part of Sweden it is around 95% due to a prolonged winter season (Trafikverket, 2021). Similarly, the use of studded tyres is common in cold climate regions, e.g., the Nordic countries (excl. Denmark), Alaska and Canada. As a result, pavement abrasion wear is a common distress in these places (Abaza et al., 2021).

Generally, municipalities in Sweden classify their street networks on the basis of their provided functions, namely, main or arterials, collectors, residential and industrial streets. Municipalities have the prerogative to decide the load-carrying

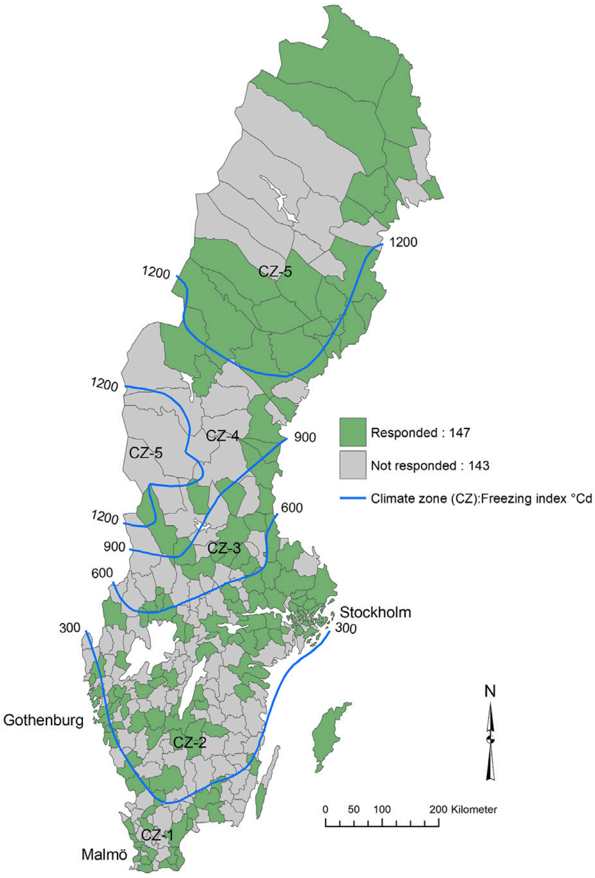

FIGURE 1
Map of Sweden showing the distribution of respondent municipalities and the five CZs based on the FI. The three biggest cities (Stockholm, Gothenburg, and Malmö) are also shown.

capacity group on their street network. Each municipality is responsible for maintaining the street network in their jurisdiction. Sweden is climatically divided into five climate zones (CZs) based on the average number of freezing degree days (freezing index, FI), i.e., from below 300 to above 1200 C ° d (Svensson, 1993; Trafikverket, 2011; Erlingsson and Saliko, 2020), namely, CZ 1 to CZ 5 (Figure 1).

The thickness of municipal pavement structure varies mainly with increased FI. Similarly, roads and streets need comparatively higher investments to build and maintain with increasing FI due to the severe climate and less competitive construction and maintenance industry. Typical pavement sections for residential streets in Swedish municipalities (Danderyd Kommun, 2011; Sandviken Kommun, 2021; Östersund Kommun, 2021; Helsingborg Kommun, 2022; Skellefteå Kommun, 2022) and state roads (Trafikverket, 2011) situated in different CZs are given in Table 1.

The thickness of the bound layers in Table 1 varies due to traffic conditions while the thickness of the subbase and frost protection layer increases with increasing FI. A geotextile on top of the subgrade is mandatory.

Pavement condition assessment is a significant step towards the effective utilization of the pavement budget. In Sweden, municipalities generally follow the locally developed guidelines of pavement condition assessment, which is useful for the visual assessment of pavement conditions (Wågberg, 2003). Similar types of guidelines have been developed in the US (Miller and Bellinger, 2014) and other European countries (Ragnoli et al., 2018). Similarly, there are locally developed guidelines to select the possible treatment alternatives for pavement distress (Wågberg, 2001). Generally, municipalities in Sweden outsource pavement condition assessment to private contractors or consultants. In fact, private vendors do not use the same methods of condition assessment, which makes it difficult for the municipalities to switch from one vendor to another (Wilén, 2016).

3 Method—Survey description

The survey presented here was composed of a questionnaire and in-depth interviews. The web-based questionnaire was sent to the customer service desk of all 290 Swedish municipalities. Thereafter, 14 in-depth interviews took place after the completion of the questionnaire. The criteria of the selection of municipalities for the interviews were solely based on the geographical location, the population size of the biggest urban area of the municipality, and the pavement network size (length per inhabitant) for streets. A total of 147 municipalities answered the survey, which yielded a 51% response rate. The geographical distribution of the municipalities is shown in Figure 1. In addition to this, 63 more municipalities had started the survey but neither finished nor submitted the survey in due time. Nevertheless, their completed parts of the survey are included in the results. Therefore, the response rate varies slightly from question to question relative to the 51% response rate. Population (SCB, 2020) and road network statistics of municipalities are presented in Table 2. As shown, the responding municipalities represent 70% of the total population in Sweden and 64% of the total municipal street network. The response rate is almost equal for all CZs, while the population density in the responding municipalities is somewhat higher than the national average.

Figure 2 highlights the research study and the results presented in this paper. Each step is described in the relevant sections.

3.1 Questionnaire content

The questionnaire was composed of 36 questions to get vital information related to the maintenance of streets owned by municipalities. The survey included: *i)* general information about municipality-owned pavement networks (8 questions), *ii)* flexible pavement condition data assessment and PMS (14 questions), *iii)* pavement distresses and their respective causes (4 questions), *iv)* budget and resources (10 questions). The question related to distresses in the questionnaire was formulated as "*How common are the following distresses on asphalt concrete street pavements*?", and was followed by a set of well-known pavement distresses (see results section). Similarly, in the case of distress causes, the question was formulated as "*How common are the following causes of distress on asphalt concrete street pavements*?". The choice of alternatives in both queries was based on a five-point Likert scale, i.e., "*None*",

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TABLE 1 Typical pavement cross-sections of municipal streets and state roads in Sweden.

	Municipal street (residential pavement cross-sections)			Low-volume state road (<5 × 10^{5} ESAL)
	CZ 1–5			CZ 1–5
	Thickness (mm)	Material	Aggregate size (mm)	Thickness (mm)
Wearing course	25–45	ABT[a]	11 or 16	45
Binder course or road base	35–60	AG[b]	16	-
Unbound base course	80–120	Crushed rock	0–32	80
Subbase	350–500	Crushed rock	0–80	420
			0–90	
			0–100	
Frost protection layer	50–650	Crushed rock	0–150	50–650
Geotextile	✓			✓
Subgrade (None to highly frost-susceptible soils)		✓		

[a]ABT, Dense Graded Asphalt Concrete pen 160/220.
[b]AG, Asphalt Gravel-Bitumen Bound pen 160/220.

"*Infrequently*", "*Quite frequently*", "*Very frequently*" and "*No info/ No opinion*". Additionally, a place for any "*Comments*" was provided to strengthen the selected answers if needed.

4 Results

The results of pavement distress, distress causes, pavement management and budget are presented as follows. Figures containing the notation N = i represent the number of responses for each option.

4.1 Pavement distresses among responding municipalities

4.1.1 Share of distress distribution

Municipalities chose the most appropriate answers to different pavement distresses among the five alternatives (Figure 3) as per the formulated question "*How common are the following distresses on asphalt concrete street pavements*?". As shown in the aforementioned figure, potholes were the most commonly cited pavement distress (80%), followed closely by surface unevenness (75%), which refers to the occurrence of pavement unevenness in both longitudinal and transverse directions due to frost heaving, corrugation and shoving. Alligator cracking, rutting and longitudinal cracking were also considered as very frequent or quite frequent distress types by a large number of survey respondents. Fewer respondents observed transverse cracking, edge deformation or ravelling, while bleeding was the least experienced pavement distress.

4.1.2 Distresses with respect to climate zones

The above data (Figure 3) was analysed further to get information about the impact of cold climate on the pavement deterioration of street networks in different CZs. In this regard, the answer alternatives "Quite frequently" and "Very frequently" to the question "*How common are the following distress on asphalt concrete street pavements?*" of the respective distress in the respective CZ were summed up and plotted against the CZs (Figure 4). It can be seen that the pothole distress occurrence increases by 75%–100% from CZs 1–5, excluding CZ 3. Similarly, surface unevenness also shows a similar trend from south to north, which is probably linked to increased frost-heave action and a higher share of studded tyre usage in the northern part of the country. The trend in the occurrence of alligator cracking is unclear, while rutting occurrence is quite similar in all CZs except for a slight drop in CZs 4–5. On the whole, the occurrence of longitudinal and transverse cracks increases from south to north, reflecting the environmental impacts on the serviceability of the pavements. Edge deformation and ravelling occurrences are infrequent, while bleeding is almost negligible distress.

4.1.3 Distresses with respect to population and road network size

The distress data (Figure 3) was further analysed to identify the impact of the frequency distribution of most cited distresses (except edge deformation, ravelling and bleeding) in relation to the population density on the road network of each municipality. In this regard, the population of each municipality was divided by its street network (km). This ratio was used to classify the population density into 5 intervals, i.e., <120, 120–160, 160–200, 200–240 and above 240 persons per km street. The results are shown in Figure 5.

The frequency occurrence of potholes and surface unevenness are very similar and it seems that both distresses increase with increasing population density. The cited trend of rutting seems also to increase with increasing population density. The occurrence

TABLE 2 Population, street network and survey statistics in the respondent municipalities.

Climate zone (CZ)	Total municipalities (no)	Total population (million)	Total street network[a] (thousand km)	Total population density on streets (persons/km)	Respondent municipalities (no)	Survey response rate (%)	Survey response rate relative to 51 per cent response (%)	Population in responded municipalities (million)	Street network in the respondent municipalities (thousand km)	Respondent municipality population density on roads (persons/km)
1	65	2.95	11.73	252	32	49	22	2.13	7.69	277
2	145	5.93	22.69	261	72	50	49	4.10	14.12	291
3	29	0.52	2.77	187	14	48	10	0.31	1.66	184
4	21	0.51	2.15	236	11	52	7	0.38	1.55	246
5	30	0.47	3.23	146	18	60	12	0.36	2.36	155
Total	290	10.38	42.57	244	147	51	100	7.28	27.37	266

[a]Partially collected from National Road Database, Trafikverket (NVDB, 2021).

frequency of alligator cracking is quite similar in all intervals while longitudinal cracking shows a trend, similar to a bell curve, that is difficult to interpret with regard to population density. On the other hand, transverse cracks show an almost uniform frequency occurrence except for the 20% decline in the most densely populated municipalities.

4.2 Share of cause of distress among the responding municipalities

In the case of common causes of pavement deterioration, the municipalities chose the most appropriate alternative among the five options to the question "*How common are the following causes of distress on asphalt concrete street pavements?*". The results are shown in Figure 6. Ageing (second-phase oxidation) was considered the most commonly cited cause of pavement distress (88%), followed closely by heavy vehicles (80%). Patching, high traffic flow and FT cycles were also indicated by a large number of survey respondents (more than 50%) as the main causes of distress. Fewer respondents observed roots and vegetation, frost heave and studded tyres among the common causes. High temperature was considered as the least frequent source of pavement distress.

4.2.1 Cause of distress with respect to climate zones

To highlight the possible impact of cold climate on the causes of pavement deterioration, the causes of distress data (Figure 6) were further analysed. In this regard, the answers ("Quite frequently" and "Very frequently") to the question "*How common are the following causes of distress on asphalt concrete street pavements*?" in the respective CZs were summed up and plotted against the CZs. The results are shown in Figure 7. Ageing was indicated as the most frequent source of pavement distress in all CZs except CZ 3. The trend suggests that ageing is almost the most significant source of deterioration in 127 municipalities located in CZs 1–2 and CZs 4–5. The low citation about ageing in CZ 3 is difficult to interpret. Heavy traffic as a source of deterioration seems to be more significant in CZs 1–2 relative to CZs 3–5. Frost heave and FT cycles are the most correlated frequent source of pavement distresses. Patching was cited in some way as an equally frequent cause of pavement deterioration. It could be associated with the abundance or presence of utility cuts, pothole fixing and localized pavement surface treatments. Studded tyres, roots and vegetation, and poor edge stability were cited as relatively low in the aforementioned sources of deterioration.

4.2.2 Cause of distress with respect to population and road network size

To highlight the possible correlation of the most cited causes of pavement deterioration to the population density on the road network, the causes of distress data (Figure 6) were further analysed. The results can be seen in Figure 8.

Ageing of pavement was cited as the most frequent source of pavement deterioration, followed by heavy vehicles and patching. Apart from a slight drop at the highest population density interval,

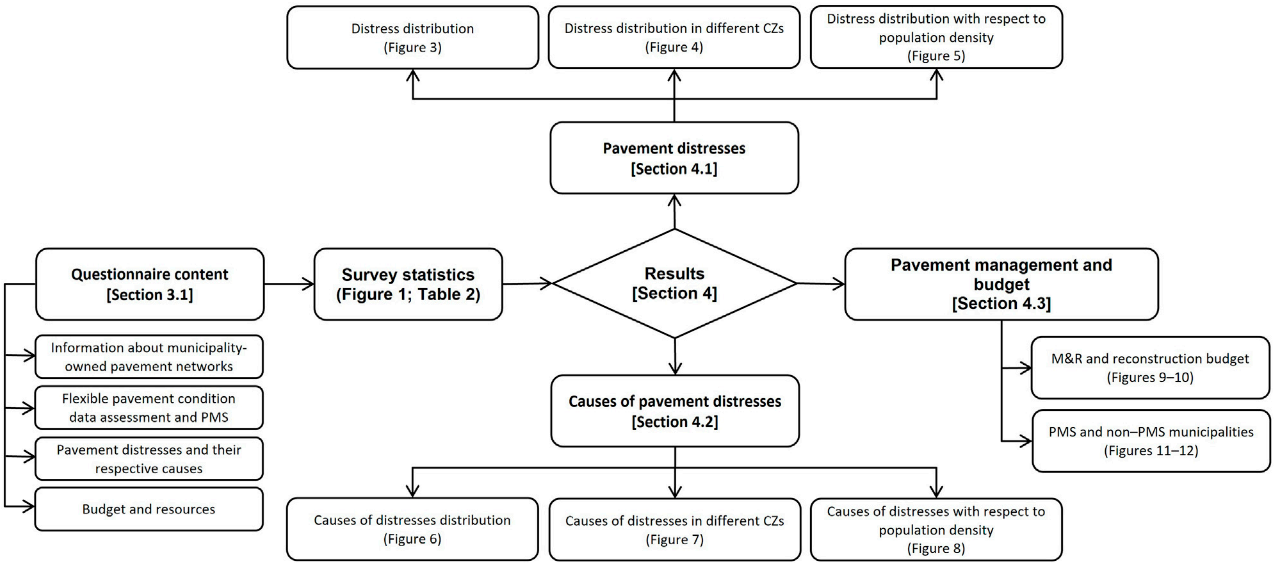

FIGURE 2
Flow chart of the study.

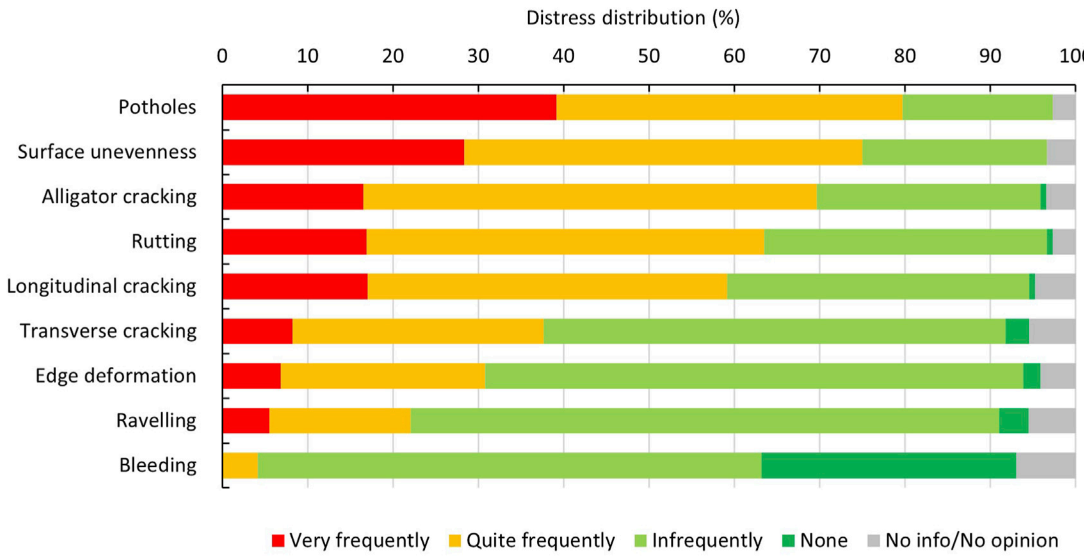

FIGURE 3
Distress distribution share among the responding municipalities.

there is an increasing trend in ageing and patching with population density intervals. Ageing, heavy vehicles, patching and high traffic flow are almost equally cited as the most frequent source of deterioration in most densely populated areas. Heavy vehicles and high traffic flow have slightly similar patterns with regard to an increase in population density intervals. The rest of the pavement deterioration causes (FT cycles, roots and vegetation, frost heave, studded tyres, poor edge stability) were cited with unclear patterns, which may be correlated with the climate rather than the population density intervals.

4.3 Pavement management and budget among responding municipalities

4.3.1 Maintenance and rehabilitation budget

The survey provides insight into the annual M&R budget allocation for the fiscal year 2020. A total of 118 municipalities reported that a total of 940 million SEK were allocated to the M&R budget to maintain about 23 thousand km of the street network (about 54% of the total street network in the country).

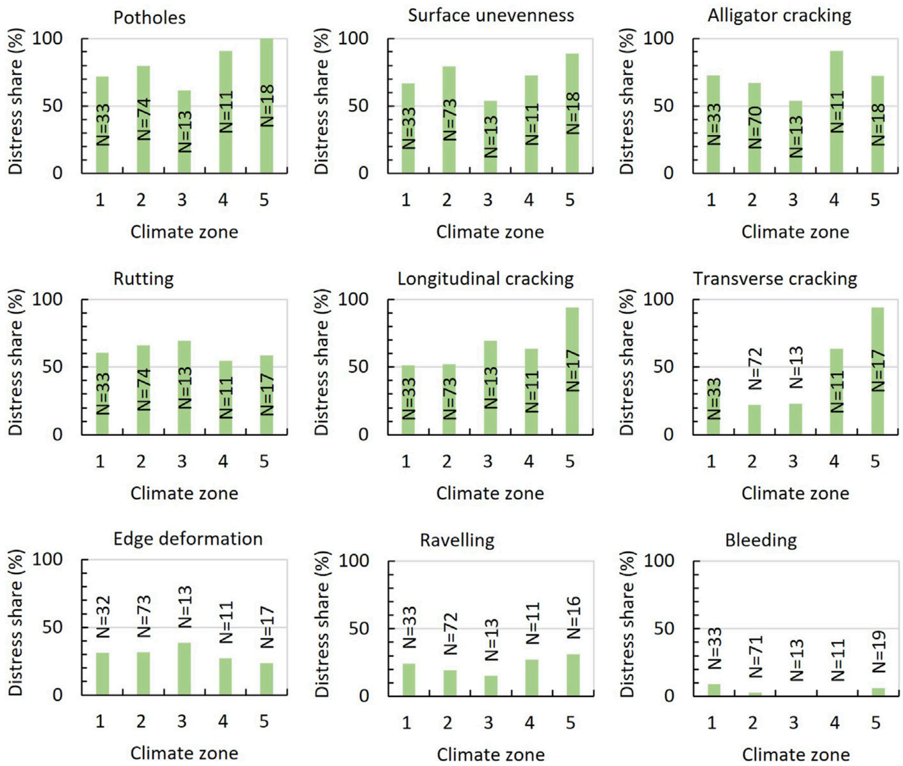

FIGURE 4
Pavement distress distribution in different CZs.

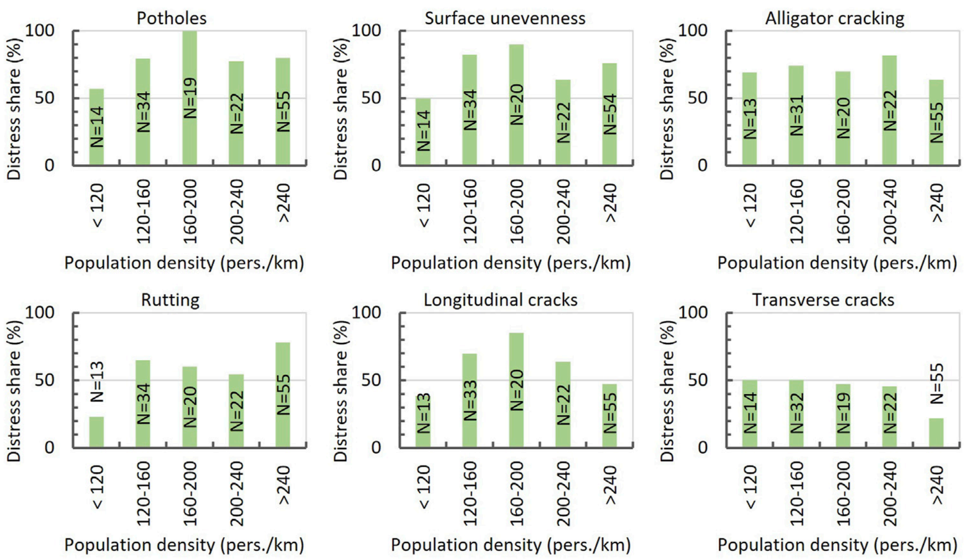

FIGURE 5
Occurrence of different pavement distresses for municipalities with respect to different population densities.

The cited M&R budget was analysed with regard to CZs and population density intervals to get an insight into the utilization of taxpayers' money on the management of the street network. In this regard, the budget of each municipality was divided by its population and the street network (km). The outcome of the taxpayers' contribution to street network management with

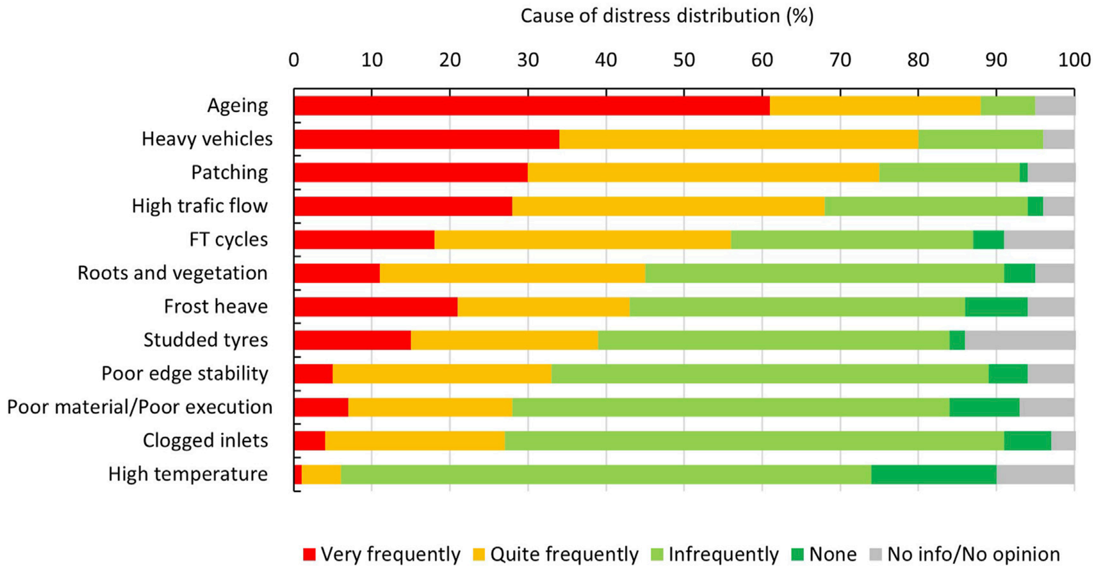

FIGURE 6
Cause of distress distribution share among the responding municipalities.

respect to CZ and population density is shown in Figure 9. It can be seen that the allocated budget for M&R activities tends to increase with an increase in FI while decreasing with an increase in population density.

The spending of taxpayers' money is highest in CZs 3–4 but lowest in CZ 2 (12 times less). On the other hand, the cited spending on M&R activities is highest in the most sparsely populated municipalities compared with densely populated municipalities. The spending trend with regard to population density seems to be strongly correlated when compared to CZ.

4.3.2 Reconstruction budget

For the fiscal year 2020, 78 municipalities cited that a total of SEK 749 million was allocated to the reconstruction budget to maintain about 16 thousand km of the street network (about 54% of the respondent municipalities). To highlight the utilization of taxpayers' money in the management of the street network, the cited spending on reconstruction activities is analysed with regard to CZs and population density. The outcome is presented in Figure 10. It is noticeable that the cited allocated expenditure on reconstruction is lower in CZs 1–2 and comparatively higher in CZs 3–5. The higher budget for reconstruction in CZ 4 (i.e., 21 times more than the CZ 2 spending) is difficult to interpret. On the contrary, the allocated budget for reconstruction decreases with an increase in population density. The most sparsely populated municipalities spent almost 14 times more than the most densely populated municipalities. Apparently, the taxpayers' spending is more associated with population density than with CZs.

4.3.3 Maintenance backlog

In response to the budget-related question, 70% of the responding municipalities cited dissatisfaction with catching up with the maintenance backlog due to the low maintenance budget. However, 25% of municipalities cited that they are satisfied in relation to their capacity and resources, while 5% were undecided. Similarly, to reduce the maintenance backlog, 34% of the municipalities indicated that they have received a budget increase over the last 5 fiscal years but it is still not enough. However,22% of municipalities cited that their maintenance budget shrank over time. One municipality cited that the maintenance backlog is huge and it is difficult to meet the performance goals even if there is enough budget, due to a lack of staff and a short summer season.

4.3.4 Pavement management

The majority of municipalities (94 out of 147) have no proper PMS in place due to a lack of resources and maintenance staff. Some municipalities even cited that the need for PMS is not required, due to the implementation cost of commercial PMS and their small pavement network. Most municipalities with no proper PMS have paper-based maintenance approaches or use spreadsheets to manage their network due to budget constraints. The budget (M&R and reconstruction) data in Figures 9, 10 have been broken down to get an insight into the role of PMS in the maintenance of the street network. The outcome is presented in Figure 11.

It can be seen in Figure 11 that the allocated M&R and reconstruction budget tends to decrease with an increase in population density, both in PMS and non-PMS municipalities. Moreover, the allocated budget for maintaining the street network is almost the same in PMS and non-PMS municipalities. It is therefore difficult to interpret or draw a conclusion about whether the cost of maintaining a street network decreases with a PMS in place or *vice versa*. Figure 12 shows the PMS and non-PMS municipalities among the responding municipalities.

It can be seen in Figure 12 that more than one-third of the respondent municipalities have a commercial PMS in place to manage 52% of the street network of respondent municipalities.

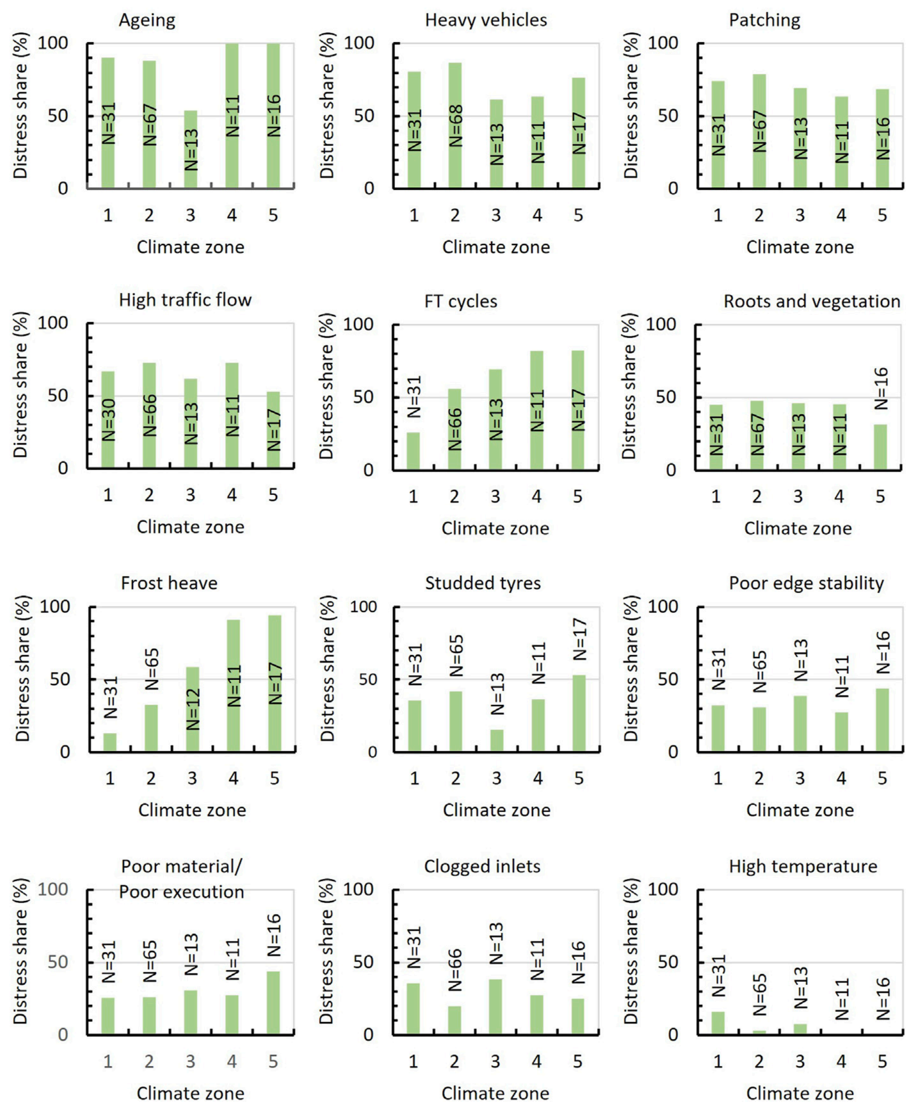

FIGURE 7
Cause of pavement distress distribution in different CZs.

The manual/windshield assessment method of condition assessment is predominant.

An annual assessment of the pavement network is most common among responding municipalities (64 out of 134) but storing such assessments is not practised. The vast majority of the PMS municipalities cited that they collected surface distress data every 4 or 5 years for the whole network. Even among PMS municipalities, storing maintenance history has not yet matured; this is a common problem among municipalities or small pavement administrations elsewhere as well.

In condition assessments, the vast majority of responding municipalities have collected the segment, type, severity and position of distress of the pavement area, as well as the functionality of the street. Nearly one-third of the responding municipalities (43 out of 147) collected data about traffic volume. However, the international roughness index (IRI) and data collection on traffic lanes, drainage inlets and side drains have never been part of the PMS among the responding municipalities. All municipalities cited that the selection of pavement segment for treatment depends on multiple factors, e.g., the type and severity of distress, the functionality of the street, traffic volume, preservation/preventive maintenance, available budget, complaints from road users, and suggestions from the municipal council.

In response to the distress analysis question, 129 out of 142 municipalities cited that they analysed the distresses through engineering judgement, even at the project level. The remaining follow locally developed guidelines and PMS recommendations. Onsite investigation or material testing happens rarely. Common pavement treatment measures that were identified include thin overlay asphalt and resurfacing after milling the deteriorated asphalt surface. Further, it was identified that pavement preservation is infrequent and is limited to cracking sealing.

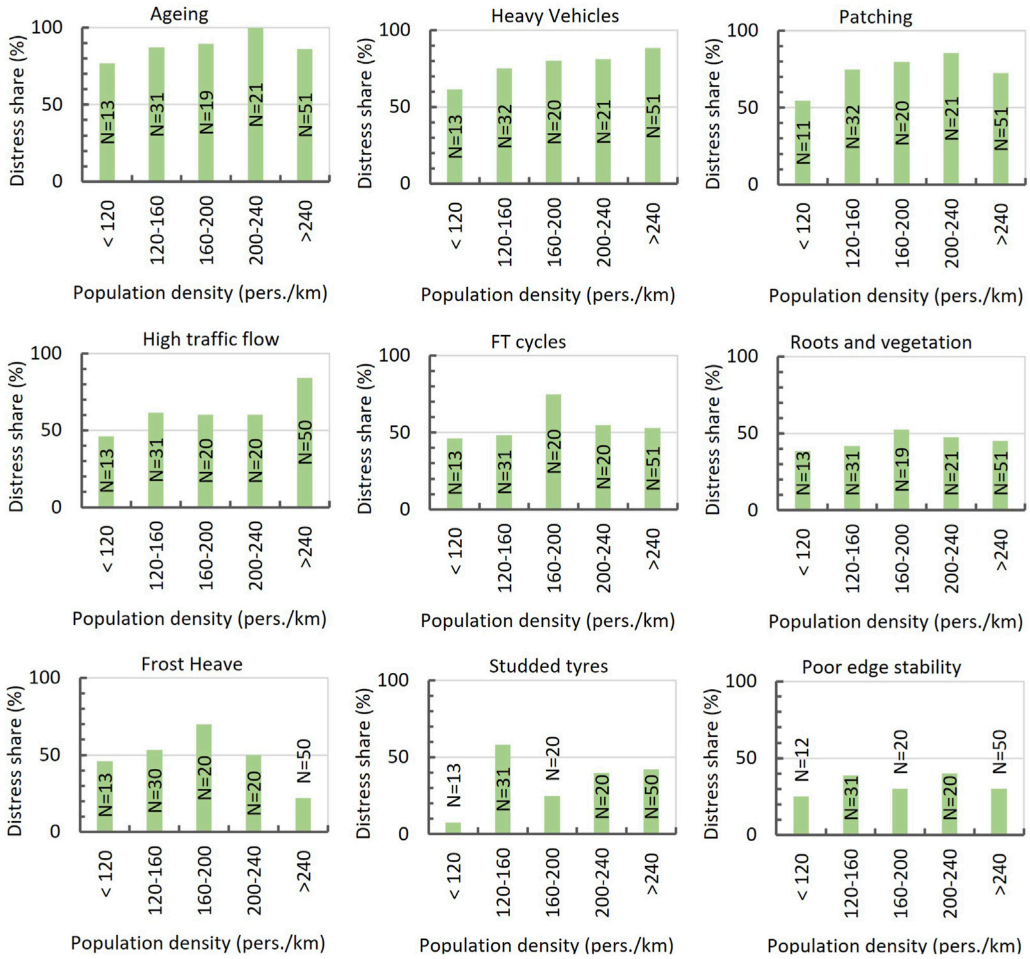

FIGURE 8
Causes of different pavement distress for municipalities with respect to different population densities.

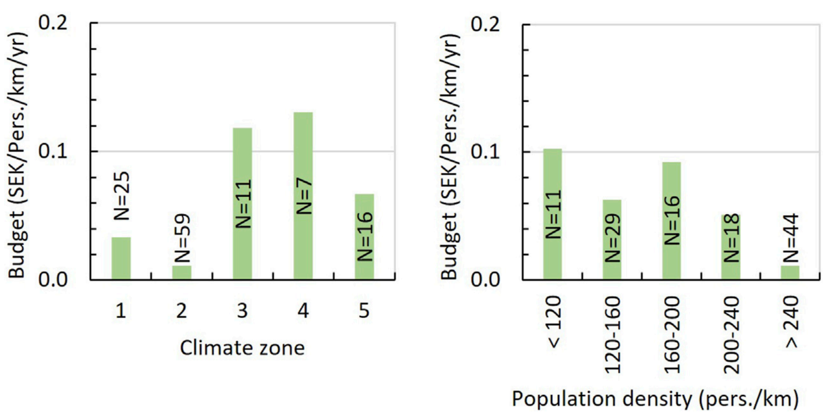

FIGURE 9
Comparison of taxpayers' contributions to streets M&R (CZ and population density).

The municipalities were asked to rank factors that could improve the current maintenance practices and street network conditions. A total of 114 municipalities indicated that the focus needs to be on the following top four areas: *i*) maintenance budget, 46% of municipalities cited that enhancement of the maintenance budget would be decisive in the matter for catching up with the

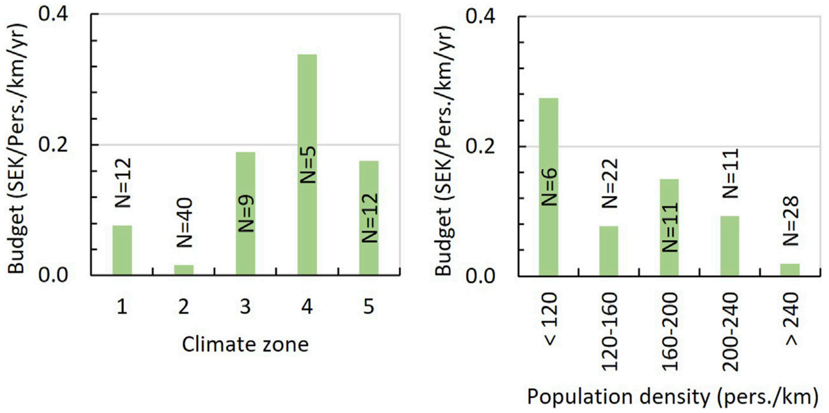

FIGURE 10
Comparison of taxpayers' contributions to street reconstruction (CZ and population density).

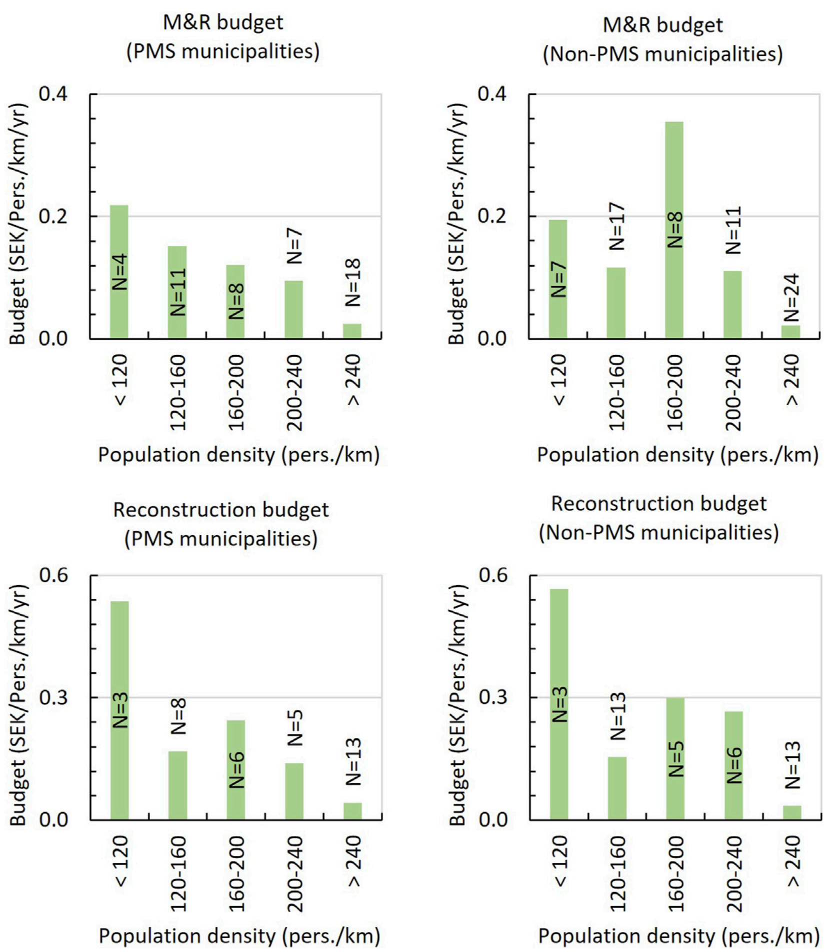

FIGURE 11
Comparison of budget in PMS and non-PMS municipalities with respect to different population densities.

maintenance backlog; *ii*) cooperation, 14% of municipalities cited that better cooperation between municipal street network administrations and utility service providers is needed; *iii*) policy guidelines, 8% of municipalities identified that better maintenance policy/guidelines from municipal councils/politicians to the municipal street network administration would lead to greater

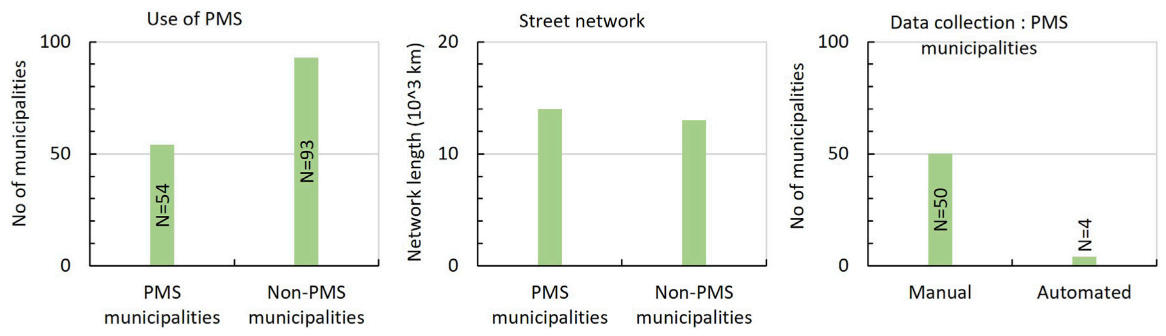

FIGURE 12
Pavement management approaches among PMS and non-PMS municipalities.

improvement; *iv*) maintenance staff, 7% of municipalities indicated that the street network condition would improve with an increase in the number of maintenance staff.

5 Discussion

5.1 Frequent pavement distress and causes

The questionnaire revealed that aged pavement as a source of pavement deterioration is the most serious issue throughout the responding municipalities (Figures 7, 8), particularly in CZs 4–5 and densely populated municipalities. This could be because of the low average frequency of resurfacing of municipal roads, since the vast majority of the municipal networks in the country were built in the 1970s. It seems that lack of resources (i.e., proper PMS usage and low frequency of pavement condition data collection) and maintenance budget play a vital role in the abundance of aged networks across the municipalities. The issue of aged pavement needs to be addressed on a priority basis since it contributes to the occurrence of several distresses.

Pavement unevenness is the second most frequent pavement distress after potholes which could be due to the combined effect of cold climate and population density on roads (Figures 4, 5). On the other hand, the occurrence of longitudinal and transverse cracks are strongly correlated to frost action or cold climate (Figure 4).

Patching is further one of the most common sources of deterioration throughout the country (Figures 7, 8). The high frequency of patching and utility cuts could be due to insufficient coordination and cooperation among street network administrations and utility service providers. The choice of material and method to repair potholes and backfill utility cuts is also decisive in keeping the functionality of the roads. In this regard, street network administrations are supposed to improve the quality assessment of backfilled materials and minimize the use of cold mix in winter due to its low durability. Additionally, to keep the street network in a serviceable condition, the street network administrators and utility service providers need to improve the share of information with each other. An integrated system or database would be useful in the timely execution of M&R activities, both for management of street networks and for utility services.

The reported occurrence of alligator cracks is surprisingly quite similar in terms of population density (Figure 5), as heavy vehicles and high traffic are cited as significant sources of distress (Figure 8). This is probably not due to insufficient asphalt-bound layer thickness (Table 1), but rather due to the abundance of aged pavements and pothole formation.

The frequency trend of rutting (Figures 4, 5) is reasonable since it reflects the significance of both cold climates (excess use of studded tyres and/or FT cycles) and the dense population density on roads. Similarly, the lowest frequency occurrence of rutting in the colder zones (Figure 4) can be related to the use of a winter road maintenance strategy, i.e., allowing snow to accumulate on the road surfaces up to a certain level. In northern Sweden, the residential streets in winter are frequently covered with snow/ice, which contributes to reducing the negative effects of studded tyres. Another reason for relatively less occurrence of rutting on municipal streets could be due to the large number of residential streets compared to main, arterial and collector streets. Residential streets are low-speed and low-trafficked streets that are mostly covered with snow, resulting in the low-frequency occurrence of abrasion wear.

5.2 Infrequent pavement distress and causes

The low-cited frequency of bleeding (Figure 4) could be related to the short summer season and the low- cited frequency of high temperatures, while the low-cited frequency of ravelling (Figure 4) might be an oversight due to the presence of issues like aged pavement, pothole formation and patches. The situation might even be the same for the roots and vegetation as a source of deterioration (Figures 7, 8). However, the low frequency of edge deformation (Figure 4) on streets could be due to the presence of pedestrian paths and houses along streets. In other words, edge deformation might be more frequent in the presence of non-functioning side drains or lack of sufficient distance between the side drain and the pavement edge. On the other hand, the reason for the low frequency of poor practices and clogged inlets (Figure 7) is difficult to interpret, since the quality standards are not the same throughout the country. Furthermore, data collection about the functionality of pavement drainage is rare.

5.3 The capacity of municipalities—strategies, resources and budget

Municipal councils, through relevant committees, decide the level of pavement performance goals and the street management budget in municipalities. Municipal pavement management staff make strategies within the available resources and budget to meet pavement performance goals. The representatives of responding municipalities realized a need for much better guidelines from the political administrations regarding the maintenance of street networks. Improvements in policies/guidelines may be achieved by presenting the current and predicted condition of the pavement network. Such assessments require the implantation of PMS.

The sophistication of the commercial PMS among the responding municipalities is low due to a lack of deterioration models, collection of roughness data, and maintenance decision rules/trees. Furthermore, a lack of maintenance history and outdated pavement data management are widespread among the responding municipalities. Consequently, it is difficult to track the quality of maintenance alternatives and maintenance practices. Annual pavement condition assessment is common but storing such data is not practised due to constraints on funding, time and resources. Subjective condition assessment and a subjective treatment selection approach are additional issues which need to be shifted to automated data collection and data-driven decision-making over time. Municipalities are generally satisfied with the current maintenance approach in relation to their competence and available budget. However, they agreed that there is room for improvement.

The street management budget reflects the approach for the utilization of taxpayers' money. The spending trend of taxpayers' money on both M&R and reconstruction activities, as per the fiscal year 2020, is similar in terms of both CZ and population density on road length (Figures 9, 10). However, the spending is 2–3 times more on reconstruction activities compared to M&R. Ideally, the spending should be more on M&R activities, though it needs a preventive maintenance approach. It can be said that the taxpayers are contributing more to the M&R and reconstruction of the municipal road network located in the northern region and sparsely populated municipalities. Timely M&R and reconstruction interventions are important in the effective utilization of the available budget, since fixing the distress in the early stage is relatively less costly.

6 Conclusion

The paper presents the results of a survey on street network deterioration and pavement management practices among Swedish municipalities. Fifty-one percent of survey responses were received out of a total of 290 municipalities across the country. The study highlights both the significant/frequent and insignificant/infrequent pavement distresses on the street network among the responding municipalities, along with the possible causes. Moreover, the study highlights the maintenance practices and the availability of budget to the municipalities to maintain the functionality and serviceability of street networks. The main conclusion of the study can be summarised as follows:

- The most cited frequently occurring distresses are potholes, surface unevenness, alligator cracking and rutting respectively.
- On the other hand, ageing, heavy vehicles, patching and high traffic flow are reported as the most frequent sources of pavement distresses.
- The use of commercial PMS is limited while visual assessment of pavements is predominant, due to budget and resource constraints.
- The M&R and reconstruction challenges varied from south to north and from sparsely to densely populated municipalities.

The share distribution of potholes, longitudinal and transverse cracking, and surface unevenness distresses tends to increase from south to north as per CZs. However, no such pattern is visible with increasing population density over road length.

Pavement age or ageing seems to be the main cause of pavement distress irrespective of CZ and population density, which reflects the high share distribution of pavement patches. This might indicate the delayed maintenance approach, possibly due to insufficient cooperation between street network and utility service administrators, a lack of resources and sophisticated PMS. Heavy vehicles and high traffic flow are almost equally dominant in terms of both population density and CZs, but the frequent occurrence of alligator cracks might be due to aged pavements. Frost heave and the number of FT cycles increases from south to north as a source of pavement deterioration. The downsides of studded tyres on residential streets are reduced due to low-speed limits and snow accumulation on street pavements.

A quarter of municipalities are satisfied with the current budget allocation for M&R and reconstruction to catch up with the maintenance backlog. Due to the short summer season and insufficient maintenance staffing, many municipalities would not be able to effectively reduce their maintenance backlog even if they have the needed budget. For the year 2020, the allocated budget both for M&R and rehabilitation decreases with increasing population density over road length, while it increases CZ-wise from southern to northern municipalities.

The challenges that the municipalities are facing are beyond pavement deterioration and cold climate. Additional challenges include getting the required pavement maintenance budget in both the short- and long-term and adapting to unclear or non-feasible maintenance policies/guidelines from municipal councils/politicians. Further challenges include developing better working procedures to improve coordination and cooperation with utility service providers, and lastly increasing the number of maintenance staff and enhancing their competence. In other words, a more national view with insights into different climate zones and capabilities of municipalities could be a good initiative in improving the safety and rideability standards on street networks.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

Conceptualization: SE, LS, and MA; Methodology: SE, LS, and MA; Investigation: MA, SE, and LS; Writing–original draft preparation: MA; Writing–review and editing: SE and LS; Visualization: MA, SE, and LS; Supervision: SE and LS; Project administration: SE and LS; Funding acquisition: SE and LS. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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