

Research Article

Types of Failure in Flexible Pavements: A Case Study of the Ethiopian Federal Road Network

**Yitagesu Desalegn Halala^{1, 2, *}, Gurmel Singh Ghataora³, Michael Burrow³,
Worku Asratie Wubet², Belayneh Desta Andarge⁴**

¹School of Engineering, University of Birmingham, Edgbaston, UK

²Ethiopian Roads Administration, Addis Ababa, Ethiopia

³Previously School of Engineering, University of Birmingham, Edgbaston, UK

⁴SMART Consulting Engineers Plc, Addis Ababa, Ethiopia

Abstract

Pavement is the hard-wearing surface built over the natural (subgrade) soil to provide a strong, stable, and smooth riding surface. A typical section of flexible pavement comprises a surface course, base course, and sub-base and subgrade layers. These layers are structured based on their load-bearing capacity (strength), with the strongest and most expensive layer at the top, and the weakest and least expensive at the bottom. However, due to several reasons attributed to the environment, traffic volume and load, subgrade condition, pavement age, construction quality control and assurance, and composition and properties of the construction and maintenance materials, asphalt pavements do not perform as expected. Accordingly, identifying the failure types is critical in understanding the contributing factors and proposing appropriate remedies. In Ethiopia, although there have been some efforts to identify pavement failure types on individual projects, no comprehensive study has been conducted to assess asphalt pavement failure types at a national or regional level. Therefore, the objective of this study was to identify the predominant Flexible pavement failure types in Ethiopia's high-traffic roads with a focus on Trunk, Link, and Main Access Roads. Self-administered close-ended questionnaire was developed and distributed to eighteen Ethiopian Roads Administration Roads Network and Safety Management Branch Office Directors and Maintenance District Directors. The questionnaire responses were analyzed using Statistical Package for the Social Sciences (SPSS) software and the relative importance index (RII). The finding showed that the primary road failure types in the Trunk, Link, and Main Access Road networks are potholes, rutting, fatigue cracking, shoving, patch deterioration, and edge break.

Keywords

Asphalt Pavement, Asphalt Road Failure, Rutting, Trunk Roads, Pavement Failure Types

*Corresponding author: desalegnyitagesu@yahoo.com (Yitagesu Desalegn Halala)

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1. Introduction

1.1. Asphalt Pavement

In highway engineering, pavement is the hard-wearing surface built over the natural (subgrade) soil to provide a strong, stable, and smooth surface for vehicles [1]. It primarily serves to distribute the applied vehicle load safely onto the larger area of the subgrade soil below and support the traffic load during the projected design life without excessive and unacceptable deformation [1].

These pavement layers are designed to protect the subgrade soil from failure when subjected to traffic loading under a given set of environmental conditions. The pavement surface should also be smooth enough to give acceptable riding comfort, provide adequate skid resistance to ensure that there is adequate friction between the wheel and road surface, and minimize traffic noise generation [2].

According to [3], a typical section of flexible pavement comprises a surface course, base course, and sub-base and subgrade layers; a typical sequence of materials is shown in Figure 1. These layers are arranged based on their load-bearing capacity (strength); the strongest and most expensive at the top, and the weakest and least expensive at the bottom. Each of the layers receives load from the upper layer transfers to the lower layer and has specific functions. The thickness of each layer depends on the strength of the subgrade soil and the functional requirements of the road.

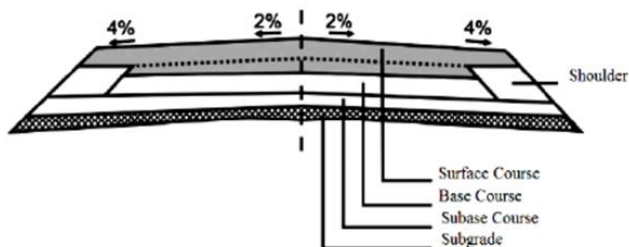


Figure 1. Typical cross section of conventional asphalt pavement [4].

The cross-section of flexible asphalt pavement shown in Figure 1 is typical of a major paved road network in Ethiopia. It is the most widely used pavement type due to its excellent performance, durability, user comfort, and ease of maintenance [5-7]. The subgrade is the bottom-most layer which provides support to the pavement serve as a foundation for the whole system, and comprise either naturally occurring or imported materials [8]. If the existing natural soil is weak, its strength may be improved by compaction, replacing weak soil with imported good quality materials, or application of ground improvement techniques such as lime/cement stabilization with the aim of achieving adequate bearing capacity to permit construction of the upper layers and providing

suitable support to the pavement system for the intended traffic loading [9]. The stiffness and drainage properties of subgrade materials determine the design of the upper pavement layers, performance, and service life [8].

The sub-base, comprising unbound granular materials, is an intermediate layer between the subgrade and base course and provides protection for the subgrade against frost, raises the overall pavement height to suit the natural water level, serves as a drainage layer, enhances the bearing strength capacity of the subgrade, improves load distribution capacity of base and surface courses and intercept migration of fine materials to the base course.

The base course provides structural support to the upper layer, transfers the load from the wearing course to the lower layers (sub-base and subgrade), shear resistance for the pavement, and intercepts migration of fine materials to the surface courses when constructed directly on the subgrade. The binder course transfers the loads from the surface course to the base course.

The surface course (also described as wearing course or friction course in some text) is the top layer of pavement structure which receives traffic load directly and provides a skid-resistant driving surface, and friction and minimizes water penetration to the lower layers [10]. A binder is placed between the base course the surface course to ensure a good bond between the two layers. In some instances, a binder layer may be placed between the base course and the wearing course.

1.2. Asphalt Pavement Performance

Asphalt pavement road is desired to provide functionally safe comfortable and long-lasting riding surfaces [5]. However, environment, traffic volume and load, subgrade condition, pavement age, construction quality control and assurance, and composition and properties of materials used for construction and maintenance affect the desired performance of the pavements [11]. According to [12], asphalt pavement failure is defined as a decrease in serviceability due to the development of distress on the surface of the pavement such as cracks, potholes, and ruts. These failures may be caused by the failure of subgrade, sub-base, base course, and wearing course or a combination of any of them [13]. Depending on its cause such as materials properties, environmental conditions, drainage conditions, and loading asphalt pavement may have different failure types [14]. Previous studies including [1, 15-18] identified various types of asphalt pavement failure types and presented in Table 1, but the authors do not give any information of classes on roads on which the failures were identifies.

Based on the above studies, the top failure types observed on the asphalt road were rutting, fatigue cracking, longitudinal cracking, potholes, shoving, raveling and weathering, and

bleeding followed by patch deterioration, polishing, edge cracking, transverse cracking, block cracking, corrugation, depression and, raveling and weathering. The identification of this failure mechanism has numerous advantages, including, improved maintenance planning, cost efficiency, enhanced road safety, informed design improvements, longer pavement lifespan, environmental benefits, and data-driven decision-making.

In Ethiopia, studies have investigated pavement failure across different road types in the network. [19] explored the Bako - Nekempte Trunk Roads network, whereas [20-22] examined Bako - Gedo, Addis Ababa- Modjo and Kemisse - Dessie Trunk Roads, respectively. These studies identified rutting, potholes, fatigue cracking, raveling, and patching as

the primary failure types that lead to the failure of the roads. Furthermore, the study by [23] identified rutting, potholes, edge cracking, transversal cracking, and raveling as the major distresses observed on the Nekempte -Bedele Link Road segment.

However, in Ethiopia, though there has been an effort to identify pavement failure types on a project basis, so far, no study has been undertaken to investigate asphalt pavement failure types on a national or regional basis. Therefore, the objective of this study was to identify the predominant failure types in the asphalt road networks of Ethiopia based on their functional classes with a focus on the Trunk, Link, and Main Access Roads.

Table 1. Asphalt Road failure types [1, 15-18].

Failure Types	Researcher (s)				
	[15]	[16]	[17]	[1]	[18]
Rutting	X	X	X	X	X
Fatigue cracking	X	X	X	X	X
Longitudinal cracking	X	X	X	X	X
Transverse cracking	X	X	X	X	
Slippage cracking	X	X	X		
Reflective cracking	X	X	X	X	
Block cracking	X	X	X		X
Edge Cracking	X	X	X	X	
Potholes	X	X	X	X	X
Shoving	X	X	X	X	X
bleeding	X	X	X	X	X
Corrugation	X	X		X	X
Depression	X	X		X	X
Delamination		X			
Raveling and weathering	X	X	X	X	X
Polishing		X	X	X	X
Patch deterioration		X	X	X	X
Stripping					X
Lane and shoulder separation			X		
Lane and Shoulder drop-off or heave			X		
Pumping and water bleeding					X
Swell		X			

2. Materials and Methods

This study was conducted in four key steps. The initial steps involved reviewing both published and unpublished literature and documents. The primary aim of this review was to identify and comprehend the different asphalt road failure types observed globally. In step 2, develop a questionnaire based on literature review and collect data with self-administered questionnaires was conducted. In step 3, the results of the questionnaire were analyzed and in step 4, conclusions and recommendations were drawn.

2.1. Functional Classification of Roads

The total road network coverage of Ethiopia at the end of 2023 was approximately 165,863 km [24]. The distribution of these roads across different administration levels (Federal, Regional, Woreda, and Municipalities) is provided in Figure 2. As shown in Figure 2, the total national road networks are shared among different administrative levels as 18.6%, 19.8%, 38.9%, and 22.7%, respectively of the Federal, Regional, Woreda, and Municipalities. However, although the Federal Road network being of lower length compared to the others it accommodates a substantial portion of the counties total traffic, both in terms of volume and magnitude of axle loads. Moreover, it plays a significant role to the economic and social development of the country through the efficient movement of freight and passengers including import and export of goods, and improving access to markets.

Generally, categorizing pavement failures by functional road class is an important part of pavement management. Functional classification accounts for variations in traffic volume, axle load intensity, speed, and strategic importance factors that significantly influence the type, frequency, and severity of pavement distresses. For example, roads in higher functional classes, which typically accommodate higher traffic volumes and heavier vehicles, are more susceptible to rutting, fatigue cracking, and structural deterioration. On the other hand, roads of lower classification are more likely to experience edge breakage, potholing, and drainage-related

damage, mainly due to poorer construction standards, inadequate maintenance, and exposure to local environmental conditions, despite experiencing lighter traffic.

Furthermore, this classification plays an essential role in guiding differentiated design and maintenance strategies. Roads in higher functional classes may necessitate enhanced subgrade stabilization, increased pavement thickness, or the use of high-performance materials such as Fiber Mastic Asphalt (FMA) to withstand loads and environmental stressors. Conversely, roads of lower classification can be effectively managed through cost-efficient surface treatments, routine patching, and improved drainage systems.

In Ethiopia, the Federal Roads are classified in terms of their function into the following classes: Trunk Roads (Class I), Link Roads (Class II), Main Access Roads (Class III), Collector roads (Class IV), and feeder roads (Class V). Each class comprise both paved and unpaved roads [25]. The design capacities for the maximum average annual daily traffic (AADT) for Classes I, II and III are 15, 000, 10,000 and 3,000, respectively. The paved segments of Classes I, II, and III (Trunk, link, and main access) account for 93.4% of the paved road network. Table 2 presents the summary of the Federal paved and unpaved road networks by functional class [26].

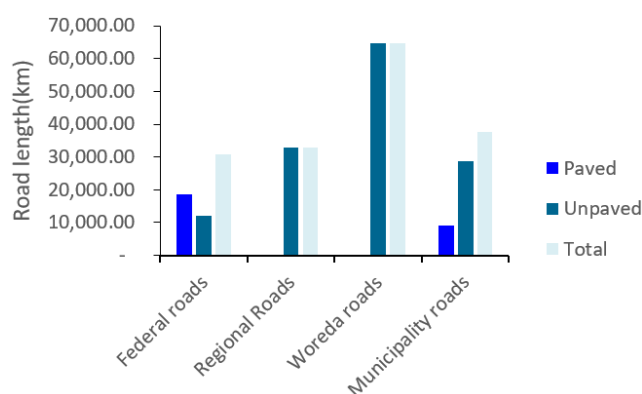


Figure 2. Detail of road networks by administrative level.

Table 2. ERA Road Network Length by Functional Classes (km).

Road Classes	Paved road (km)	Unpaved road (km)	Total (km)	Percentage of paved roads (%)
Trunk	7,581.78	1,127.59	8,709.37	41.3
Link	7,531.79	5,139.56	12,671.35	41
Main access	2,041.80	3,198.00	5,239.80	11.1
Collector	936.27	2,016.39	2,952.66	5.1
Feeder	63.45	127.53	190.98	0.3
Unclassified	216.82	459.51	676.33	1.2
Total	18,371.91	12,068.58	30,440.49	100

The above road networks are distributed throughout the country and managed by eleven Road Network and Safety Management Branch Offices (RNSMBO). Each RNSMBO is responsible for the management and maintenance of their roads. The total length of roads covered by each RNSMBO [27] is shown in Figure 3.

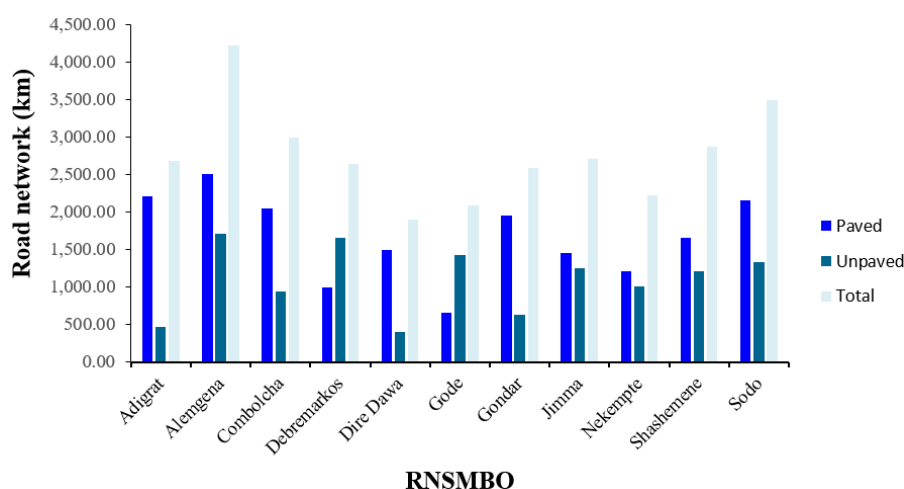


Figure 3. Road network coverage by RNSMBO.

2.2. Data Collection

Self-administered close ended questionnaires were used to gather data as noted in section 2, above. The questionnaires were designed with a 5-point Likert's scale of 1 to 5 where 1. represents Uncommon (less than 10%), 2. less common (up to 20%), 3. common (up to 35%), 4. very common (up to 66%), 5. most common (more than 66%). The percentages given in the scale relate to total failures on the particular road type. The respondents were asked to vote using a color system or selecting appropriate boxes using any of the provided electronic or hard copy forms using 1 to 5 scale.

The respondents for the questioner survey were selected using census techniques. A census approach was adopted due to the limited size of the target population. When the total number of potential respondents is relatively small and each individual is known to have valuable, expert-specific, or context-rich information it is practical and methodologically sound to include the entire population in the data collection process. The target population includes all Ethiopian Roads Administration Road Asset Management Department, RNSMBO and Road Maintenance District (RMD) Directors. As verified from ERA organogram and responsibility matrices, these directors were responsible for road condition survey, maintenance planning and maintenance of road networks and road infrastructure asset managements. Thus, the selected participants ensured that the survey reflected the informed perception supported by adequate experience and needed information.

2.3. Data Analysis

Five senior professionals from the road sector and aca-

demia verified the chosen methods, techniques, procedures, and questionnaire. Both stripping and edge drop were added to the original list of failure types based on the advice of the senior professionals.

The internal consistency (reliability) of the study was assessed by Cronbach's alpha (α) reliability coefficient, using Equation 1 [28]. The Cronbach's alpha reliability coefficient typically ranges from 0 to 1, with high values indicating higher reliability of the questionnaire [29, 30]. According to [31], a Cronbach's alpha score of 0.67 or higher is acceptable, while a score of 0.80 or above is excellent. The Cronbach's alpha score was determined using the Statistical Package for the Social Sciences (IBM SPSS Statistics 26).

$$\text{Alpha}(\alpha) = N\bar{c}/(\bar{v} + (n - 1)\bar{c}) \quad (1)$$

Where:

N represents the number of items, $\bar{v}$ is the average variance, and $\bar{c}$ refers to the average inter-item covariance among the items.

Accordingly, Cronbach's α reliability coefficients of 0.834, 0.878, and 0.895 for the Trunk, Link, and Main Access Roads, respectively, were obtained for 24 options. All these values are within the excellent range [31] indicating that the research tool had high internal consistency and suitable for further analysis.

The questionnaire responses were analyzed using the Relative Importance Index (RII). The RII is a statistical method used to rank various factors according to their level of importance or priority [32]. The Relative Importance Index (RII) was selected as the primary analysis tool since it is suitable to address the study objective. Specifically, RII facilitates the conversion of qualitative expert opinions collected through

Likert-scale surveys into a structured, numerical format. This makes it appropriate for evaluating subjective assessments. By enabling the systematic ranking of pavement failure types based on expert judgment, the RII method directly supports to prioritize the different types of pavement distress. The RII for each failure types were determined with Equation 2 using Microsoft Excel [33].

$$\text{RII (\%)} = \frac{5(n_5) + 4(n_4) + 3(n_3) + 2(n_2) + n_1}{5N} \times 100 \quad (2)$$

Where:

n_1 to n_5 represent the number of respondents who selected a scale 1 to 5 for not common, less common, common, very common and most common, respectively.

N is the total number of received responses (i.e., 18 for the Trunk and 17 for the Link and Main Access Roads).

RII ranges from 0 to 1 where the higher values take priority. [34, 35] classified the RII into five priority levels; high ($0.8 \leq \text{RI} \leq 1$), high to medium ($0.6 \leq \text{RI} \leq 0.8$), medium ($0.4 \leq \text{RI} \leq 0.6$), medium to low ($0.2 \leq \text{RI} \leq 0.4$) and low ($0 \leq \text{RI} \leq 0.2$).

2.4. Ethical Consideration

The questionnaire survey was based on key ethical principles which included voluntary participation, anonymity, confidentiality, informed consent, risk of harm, and the communication of findings [36]. As such, any information entrusted to the researcher was treated confidentially and used exclu-

sively for the intended purpose. Respondents were informed about the voluntary nature of their participation, the purpose of the study, potential risks, confidentiality, the expected benefits of the study, and their right to withdraw their information within two weeks of submission. All the data and findings were randomized, anonymized, such that it could be used to identify an individual and all secondary data used in the study were properly credited and cited, with authors acknowledged and references provided.

3. Results and Discussion

Eighteen questionnaires were distributed electronically, to Ethiopian Roads Administration RNSMBO and RMD Directors. Eighteen responses for Trunk and seventeen for Link and Main access road networks were collected through email resulting in a response rate of 100% and 94%, respectively.

The overall findings of the questioner survey revealed that asphalt road failure in Ethiopia manifests in various forms including rutting, cracking (fatigue, transverse, longitudinal, slippage, reflective, edge and block), potholes, shoving, raveling, and weathering, corrugation, depression, stripping, polishing, delamination, bleeding, patch deterioration, segregation, pumping and water bleeding, swell, edge drop off, lane or shoulder drop off or heave, lane and shoulder separation. The RII and ranking of each failure types for the Trunk, Link and Main access road networks are given in Table 3.

Table 3. Ranking based on Relative Importance Index.

Failure Mechanism	Trunk Road		Link Road		Main Access Roads		Mean	
	RII	Rank	RII	Rank	RII	Rank	RII	Rank
Rutting	0.744	2	0.600	2	0.567	3	0.637	2
Fatigue cracking	0.700	3	0.578	4	0.544	5	0.607	3
Longitudinal cracking	0.567	7	0.500	11	0.467	13	0.511	11
Transverse cracking	0.489	16	0.467	15	0.467	13	0.474	15
Slippage cracking	0.444	17	0.411	21	0.444	15	0.433	17
Reflective cracking	0.444	17	0.411	21	0.389	22	0.415	21
Block cracking	0.511	13	0.489	13	0.411	21	0.470	16
Edge Cracking	0.611	6	0.533	7	0.589	2	0.578	6
Potholes	0.778	1	0.756	1	0.711	1	0.748	1
Shoving	0.633	5	0.589	3	0.544	5	0.589	5
bleeding	0.522	11	0.433	16	0.500	9	0.485	13
Corrugation	0.511	13	0.522	8	0.544	5	0.526	9
Depression	0.522	11	0.511	10	0.522	8	0.519	10
Delamination	0.422	19	0.433	16	0.422	19	0.426	19

Failure Mechanism	Trunk Road		Link Road		Main Access Roads		Mean	
	RII	Rank	RII	Rank	RII	Rank	RII	Rank
Raveling and weathering	0.567	7	0.522	8	0.500	9	0.530	7
Polishing	0.367	23	0.356	24	0.356	24	0.359	24
Patch deterioration	0.656	4	0.578	4	0.567	3	0.600	4
Stripping	0.422	19	0.422	19	0.389	22	0.411	22
Lane and shoulder separation	0.511	13	0.500	11	0.478	12	0.496	12
Lane and Shoulder drop-off or heave	0.544	9	0.478	14	0.433	17	0.485	14
Edge drop-off	0.544	9	0.544	6	0.500	9	0.530	8
Segregation	0.422	19	0.433	16	0.433	17	0.430	18
Pumping and water bleeding	0.367	23	0.367	23	0.422	19	0.385	23
Swell	0.411	22	0.422	19	0.444	15	0.426	20

The finding from RII analysis showed that the predominant failure types of the asphalt road networks of Ethiopia were potholes (RII = 0.748) rutting (RII= 0.637), fatigue cracking (RII=0.607), patch deterioration (RII=.600) and shoving (RII=0.589). All these failures were classified within high to medium priority level, with shoving being rated as medium level). Summary of the top most five predominant asphalt road failure types along with the priority levels are presented in Table 4.

Table 4. Predominant asphalt failure types, RII and priority Level.

Failure types	RII	Priority level
Potholes	0.748	High to Medium
Rutting	0.637	High to Medium
Fatigue cracking	0.607	High to Medium
Patch deterioration	0.600	High to Medium
Shoving	0.589	Medium

For the Trunk Road networks, the analysis identified potholes (RII=0.778), rutting (RII=0.744), fatigue cracking (RII=0.700), patch deterioration (RII=0.656), and shoving (RII=0.633) as the predominant failure types. For the Link Road, the prevalent failure types were potholes (RII=0.756), rutting (RII=0.600), shoving (RII=0.589), fatigue cracking (RII=0.578), and patch deterioration (RII=0.578) whereas, for the main accesses road it was found potholes (RII=.711), edge cracking (RII= 0.589), rutting (RII=0.567), patch deterioration (RII=0.567), fatigue cracking (RII=0.544), shoving

(RII=0.544) and corrugation (RII=0.544).

When comparing Main Access Roads to Trunk and Link roads, it frequently lacks adequately constructed shoulders. On many occasions, the shoulders are either narrow, unpaved, or absent without proper support, and the pavement edge becomes highly prone to deformation under repeated heavy vehicular loading. This repeated stress at the unsupported edge leads to longitudinal cracking over time. In addition to structural shortcomings, the geometric design of Main Access Roads is usually constrained by budgetary limitations, resulting in reduced pavement widths. These narrow widths force vehicles to travel closer to the pavement edges during bidirectional traffic flow. As a result, the edges are exposed to higher stress concentrations compared to the central portions of the pavement. This uneven load distribution further accelerates deterioration, making edge cracking a common issue on Main Access Roads.

Furthermore, the identified failure types for Trunk Roads are consistent with previous studies including [19, 20]. Additionally, the most rated failure types for all classes are mainly associated with traffic, environment such as temperature, lack of maintenance and poor maintenance practice. In contrast, the research conducted by [37] on Obeid Khatim Road in Khartoum, Sudan, reported that fatigue cracking, rutting, block cracking, edge cracking, and potholes were the most frequently observed pavement distresses in deteriorated sections. These results differ from the findings of the current study, especially regarding secondary failure types (potholes). Potholes were ranked fifth in this study's assessment, while it was ranked first in the current study for all three road classes. Furthermore, block cracking was identified among the top five failure types in the referenced work. Such discrepancies could be due to the influence of a range of contributing factors, including differences in traffic volume and loading condition, road classification, construction standards, and maintenance

practices. These contextual variations highlight the importance of considering local conditions when evaluating pavement performance and failure mechanisms.

Potholes can be considered to secondary modes of failure as they can be initiated by combination of cracking, ingress of water and possibly deformation leading to local disassembly of the pavement structure. If untreated, potholes can grow rapidly leading significant loss of performance of road and increase in road user cost. Thus, it may be prudent to deal with the primary failures that lead to formation of potholes at both the design, construction and maintenance stages as appropriate [38]. The top four priority listed in Table 4 (potholes, rutting, fatigue cracking, and patch deterioration) need to be addressed as a matter of priority through improvements in relevant design standards, timely maintenance, use of appropriate materials and methodologies for both construction and maintenance.

4. Conclusions

This study was undertaken to identify the prevalent modes of failure in the asphalt roads in Ethiopia. It was based on a questionnaire survey of all the road network regions in the country and included three road types: Trunk, Link and Main Access Roads, which consists of about 93% of the Federal paved road network.

The following conclusions were drawn.

- 1) 22 types of road failures were identified in all the regions.
- 2) Potholes were the most predominant pavement failure mode for all types of roads in all regions.
- 3) For Trunk Roads and Link Roads rutting was the next more frequent failure mode whereas edge cracking was the next most important mode.
- 4) The third most prevalent mode of failure for Trunk and Main Access Roads was fatigue cracking. For Link Roads shoving was the next most important.
- 5) Potholes, rutting, fatigue cracking, and patch deterioration were high level of priority indicating the importance of need to improved design standards, timely maintenance, use of improved construction materials and construction techniques to enhance the longevity of the asphalt pavements thereby reduce rehabilitation and reconstruction costs.

Abbreviations

AADT	Average Annual Daily Traffic
AASHTO	American Association of States Highway Transport Official
CBR	California Bearing Ratio
ERA	Ethiopian Roads Administration
RMD	Road Maintenance District
RNSMBO	Road Network and Safety Management Branch Office

RSDP Road Sector Development Program

Declarations

Availability of data and materials: The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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Author Contributions

Yitagesu Desalegn Halala: Conceptualization, Data curation, Formal Analysis, Methodology, Writing - original draft, Writing - review & editing

Gurmel Singh Ghataora: Conceptualization, Formal Analysis, Methodology, Writing - review & editing

Michael Burrow: Conceptualization, Formal Analysis, Methodology, Writing - review & editing

Worku Asratie Wubet: Conceptualization, Methodology, Writing - review & editing

Belayneh Desta Andarge: Formal Analysis, Writing - review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Yitagesu Desalegn Halala MSc. Ethiopian Roads Administration

Gurmel Singh Ghataora PhD. Previously at the University of Birmingham

Michael Burrow PhD. Previously at the University of Birmingham.

Worku Asratie Wubet PhD. Ethiopian Roads Administration

Belayneh Desta Andarge MSc. SMART Consulting Engineers plc