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A participatory data-driven approach for unpaved road condition monitoring

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ABSTRACT

Unpaved roads, usually found in rural and sparsely populated areas, are prone to dust, potholes, corrugations, rutting and loose gravel and deteriorate faster than paved roads. Thus, they require regular condition monitoring to keep them at the required level of service. However, the cost of condition assessment could be huge, considering how vast and far away they are from the cities. Currently, subjective visual surveys and manual methods for monitoring and assessing the condition of unpaved roads dominate, while data-driven objective methods are not commonly applied for maintenance planning and decision-making. The paper proposes a participatory data-driven approach for unpaved road condition monitoring based on the literature and an exploratory case study of road maintenance practices in Sweden and Zambia. Participatory data collection empowers regular unpaved road users to collect road condition data, for instance, by equipping their vehicles with the relevant data acquisition devices embedded with a global positioning system (GPS) as they drive on unpaved roads on a typical day. By integrating open data collection aligned with sustainable practices, regular unpaved road users (garbage collectors, postal service providers, and road owners) share the collected condition data with the road governing bodies and process it for Nowcasting and Forecasting the unpaved road condition, thus providing valuable information for condition monitoring of unpaved roads. Thus, road users can support long-term maintenance planning and decision-making, potentially improving unpaved road management and minimising the cost of collecting and evaluating unpaved road condition data. However, the participating road users require training in data acquisition, and the vehicles must be calibrated according to the sensor properties, vehicle vibration response and speed to ensure quality data collection. Based on the literature and the case study findings, participatory data collection for unpaved roads can provide an efficient and effective alternative for collecting road condition data, accomplishing broad coverage.

Keywords: Condition monitoring, forecasting, gravel roads, nowcasting, participatory data collection, unpaved roads

1. INTRODUCTION

Regular maintenance of unpaved roads is considered necessary to maintain the road network satisfactorily. While this is generally true for unpaved roads, national strategies and managerial practices differ. For instance, gravel roads, a common type of unpaved road widespread in Sweden, account for about 20% of the road maintenance budget in Sweden (Alzubaidi, 1999). Municipalities, road owners and maintainers are responsible for ensuring the gravel roads are maintained to an acceptable service level. They receive financial support from the Swedish government. In Zambia, the Roads Development Agency (RDA), a government-funded agency, is tasked with maintaining all roads for safety, driving comfort and environmental sustainability. According to Kasongo (2015), most of Zambia's unpaved roads are deplorable and makeup about 75% of the core road network, which is approximately 33,000 km long. RDA conducts annual surveys to determine the condition of unpaved roads (Mwanaumo and Sakala Sakala, 2021). These governing bodies have scarce resources to invest in costly complex technical solutions and other competing needs and therefore seek prudent use of resources by minimising maintenance costs and striving to provide good unpaved roads (Kans *et al.*, 2022; Mbiyana *et al.*, 2022).

Mbiyana et al. (2022) proposed the need for further research on cost-effective and efficient objective data-driven assessment methods for low-traffic roads through conceptual development, prototyping, and predictive and prescriptive model development that match actual needs and user requirements. Participatory data collection employing technological advancements and open data collection that aligns with sustainable practices is one of the proposed cost-effective methods for assessing unpaved roads. Although not relatively new, the participatory data collection concept has not been exploited for unpaved road maintenance (Nunes and Mota, 2019). Regular unpaved road users and road owners can be empowered to collect and share the collected road condition data with the road governing body on a shared server or via a cloud-based system. The data can then be used for road condition assessment and maintenance optimisation. However, it must be ensured that the training of the participants should result in the collection of high-quality data and that their privacy is guaranteed (Kanhere, 2013). Other factors to consider in ensuring quality data collection include the sensor properties, vehicle vibration response and speed (Aleadelat *et al.*, 2018; Wang *et al.*, 2020).

The main research question is: *How can participatory condition monitoring be developed into an efficient and effective data-driven approach for unpaved road maintenance to enhance condition monitoring?* The paper proposes a participatory data-driven approach for assessing the condition of unpaved roads based on literature and an exploratory case study on Sweden and Zambia. The proposed approach implies that assessors will not have to travel on-site for road condition inspection and data collection but can utilise the data frequently collected by road users to assess the road condition. Implementing a participatory data-driven approach for condition monitoring of unpaved roads would improve unpaved road management regarding condition data collection, maintenance costs and ride comfort.

2. LITERATURE REVIEW

Unpaved roads provide access to low-traffic areas, mainly rural areas, positively impacting socio-economic living conditions and are essential for agriculture, wildlife and tourism, and forestry (Marinello *et al.*, 2017). When rural roads are adequately maintained, production efficiency is improved, goods and service delivery is enhanced, and residents are empowered (Abbas and Kans, 2022). Unpaved roads have a higher deterioration rate than paved roads, necessitating frequent regular condition monitoring and data collection, and are prone to dust, potholes, corrugations, rutting and loose gravel (Huntington and Ksaibati, 2015; Kans *et al.*, 2020a). In addition, maintaining an unpaved road to a high standard demands frequent maintenance, which increases maintenance costs. A compromise of the level of service has to be found while still achieving the required ride comfort and safety (Abbas and Kans, 2022). Figure 1 shows various unpaved road defects: Pothole (a), corrugations/washboardings (b), loose gravel (c) and dust (d). The road roughness resulting from a combined effect of different unpaved road defects influences the ride quality (Aleadelat *et al.*, 2018). At the same time, dust causes respiratory health complications in humans and animals and impairs drivers' vision, thereby contributing to road traffic accidents (Edvardsson and Magnusson, 2009). In addition, the photosynthetic activities of plants and crop yield are reduced for plants near unpaved roads (Albatayneh *et al.*, 2019).

(a) (b) (c) (d)

Figure 2. (a) Pothole, (b) corrugations, (c) loose gravel and (d) dust on unpaved roads

Data and model-driven approaches can be utilised for now-casting and forecasting the condition of unpaved roads based on data collected using smartphones by exploiting signal processing, machine learning, digitalisation, and artificial intelligence. Now-casting involves predicting the present and near future state and performance of an asset assessed against the Key Performance Indicators (KPI) set out for that particular asset and provides insight into what has happened and why it has happened (Bragoli and Modugno, 2017). Forecasting involves making an informed estimation of an asset's future state based on historical data, present data and the knowledge of future factors that may impact the forecast (Hyndman and Athanasopoulos, 2018). Quality historical condition data is essential for accurate decision-making and road classification (Oladele *et al.*, 2014). Therefore, the accuracy of the now-casting and forecasting is influenced by the availability and sufficient of relevant data.

Although there is active research in the area, objective unpaved road data collection, assessment and condition monitoring have not been holistically applied in the maintenance process of unpaved roads (Mbiyana *et al.*, 2021). Therefore, there is a lack of high-quality and relevant data on unpaved road conditions as the assessment methods are mainly visual surveys (Van Der Gryp and Van Zyl, 2007; Jones *et al.*, 2003; Jones and Paige-Green, 2000) prone to subjectivity and human judgment error (Saeed *et al.*, 2022). Manual assessment using cost-effective equipment like profile walkers is time-consuming while deploying unmanned aerial vehicles (UAVs) in adverse weather conditions is challenging (Kans *et al.*, 2020a). On the other hand, objective condition assessment methods for paved roads cannot be directly applied to unpaved roads due to the differences in failure propagation, degradation mechanisms and the working environment (Kans *et al.*, 2020a). The readings could be inaccurate, and the dust and water could damage the measuring equipment and sensors on the road (Kans *et al.*, 2020b). Furthermore, the substantial investment cost of the complex equipment is not economical for low-volume unpaved roads, thus a significant drawback to road agencies (Mbiyana *et al.*, 2022).

Nevertheless, technological advances, particularly sensor technology in mobile phone technology and information and communication technology (ICT), have opened new avenues for large-scale condition monitoring and data collection (Kumari *et al.*, 2022). These advances have also increased data availability and cost-effective and efficient data processing algorithms (Kumari *et al.*, 2022). Recently, there has been a growing research interest focused on objective assessment methods using data-driven methods (DDMs) and knowledge of image processing, vibration and acoustics analysis; however, implementation in unpaved road maintenance is lacking (Mbiyana *et al.*, 2022). Participatory data collection is one of the new ways for large-scale condition data collection, allowing ordinary citizens to be a part of the maintenance process by collecting and sharing road condition data, for example, with their smartphones (Campbell *et al.*, 2008; Kanhere, 2013; Kim *et al.*, 2016).

A smartphone camera can be used as a video and image sensor, the microphone as an acoustic sensor, and embedded gyroscopes and accelerometers to measure the slope and road vibration, respectively. At the same time, the GPS receivers can provide information about the location of the measured condition data. Smartphones offer a cost-effective solution for the condition data collection on unpaved roads (Mbiyana *et al*., 2022). They have been applied to estimate road surface roughness and ride quality (Aleadelat *et al*., 2018). Around 5 billion people worldwide can access mobile phones, offering unique and broader coverage and reduced implementation costs (Kanhere, 2013).

Participatory data collection has been applied for personal health monitoring, air quality monitoring, real-time traffic statistics and noise mapping (Kanhere, 2013; Nunes and Mota, 2019). For instance, drivers can access real-time traffic and acclimatise or change their routes (Nunes and Mota, 2019). For improved accuracy, participants share the collected individual data, which is then aggregated to provide useful information for the stakeholders (Nunes and Mota, 2019). Kim et al. (2016) applied participatory data collection as a human-centred sensing approach to detect defects on sidewalks by monitoring pedestrians' physical behaviour using an inertial measurement unit (IMU) sensor and a GPS on a smartphone. The locations showing irregularities in the pedestrian-response patterns indicate the presence of a defect.

Streetcheck, an offline mobile classification system, is used by Nunes and Mota (2019) as a participatory sensing framework based on data obtained and shared by participants to classify urban road surfaces. Streetcheck collects, filters, processes and classifies the data into a map view of the classified routes. According to Nunes and Mota (2019), although participatory data collection has been widely used for real-time traffic monitoring, this is not true for road surface quality data. The issues of sensor accuracy, privacy and the standard definition of quality have posed challenges to implementation (Nunes and Mota, 2019). Furthermore, the International Roughness Index (IRI) requires special, costly equipment calibrated and mounted on special vehicles and skills that ordinary drivers with their smartphones cannot have.

3. RESEARCH METHODOLOGY

The paper attempts to develop a participatory data collection approach for monitoring the condition of unpaved roads based on a literature review and an exploratory case study of unpaved road maintenance in Sweden and Zambia. The literature review covered unpaved road maintenance and condition monitoring, data-driven maintenance and participatory data collecting. The literature review results defined the interview questions; see the attached Appendix. The questions were intended to provide an overview of unpaved road maintenance practices in Sweden and Zambia and their view on implementing participatory data collection to support long-term maintenance planning and decision-making of unpaved roads. The structured yet open-ended questions provided the respondents with long and detailed responses. Prior to the data collection, a questionnaire was created in a Google form and shared with the respondents. The concepts of data-driven maintenance and the standard Open System Architecture for Condition Based Maintenance (OSA-CBM) are utilised to develop a participatory data-driven approach to collect data on the condition of unpaved roads.

3.1 Case study – Sweden and Zambia

The Swedish Transport Administration (Trafikverket) was one of the respondents to the questionnaire. In Sweden, the transportation sector and state-owned roads are managed by Trafikverket, which also regulates and finances the maintenance of private-owned gravel roads eligible for financial support. A focus group of five Trafikverket employees involved in the gravel road maintenance process was constituted to answer the Google form questionnaire. The other respondent, the Swedish National Road and Transport Research Institute (VTI) is charged with conducting research and development work in Sweden's transport sector. From VTI, two respondents whose research relates to road traffic were identified. A detailed one-on-one interview and discussion with staff from the Roads Development Agency (RDA) in Zambia, which oversees the Rural Road Unit, was conducted using the same questionnaire for Trafikverket and VTI. One of RDA's obligations is maintaining Zambia's public roads, including unpaved ones. A senior official was interviewed and gave a broader view of the maintenance practices on rural roads in Zambia and their opinion on implementing participatory data collection.

4. CASE STUDY FINDINGS AND DISCUSSION

After compiling the findings from Sweden and Zambia, the maintenance practices of the two countries were compared, complemented by the literature study on rural roads in Sweden and Zambia. The results are presented in this section. The questions asked are assigned Q1 to Q20 for questions 1 to 20. The order of the questions in the questionnaire can be found in the Appendix. The responses are in the results section for each case (Sweden and Zambia). The outcome of the case study was the basis for the proposed participatory data-driven approach for unpaved road condition monitoring. It also helped to identify gaps in the maintenance process, although these are not discussed in detail in this paper.

4.1 The Sweden Case

The Swedish Transport Administration (Trafikverket) was one of the respondents to the questionnaire. In Sweden, the transportation sector and state-owned roads are managed by Trafikverket, which also regulates and finances the maintenance of private-owned gravel roads eligible for financial support. A focus group of five Trafikverket employees involved in the gravel road maintenance process was constituted to answer the Google form questionnaire. The other respondent, the Swedish National Road and Transport Research Institute (VTI) is charged with conducting research and development work in Sweden's transport sector. From VTI, two respondents whose research relates to road traffic were identified. A detailed one-on-one interview and discussion with staff from the Roads Development Agency (RDA) in Zambia, which oversees the Rural Road Unit, was conducted using the same questionnaire for Trafikverket and VTI. Trafikverket is responsible for operating and maintaining the national road network, which consists of approximately 100,000 kilometres (km) of roads.

Of these, about 20,000 km are gravel roads. Gravel roads exist throughout the country, but 60% of the length of the gravel road is in the North (Norrbotten and Västerbotten counties) and Central (Dalarna, Gävleborg, Jämtland and Västernorrland counties) regions. In addition, Trafikverket pays grants to private road owners with a total road length currently around 75,000 km as subsidies for gravel road maintenance [Q1]. Kans et al. (2020b, 2021), Kuttah (2016), and Saeed et al. (2020) report similar figures for the gravel road mileage in Sweden. Gravel roads are essential for business (e.g. forestry), i.e. timber transportation, and contribute to an excellent, accessible, traffic-safe road system across the country, especially for those living and working in the countryside [Q2]. The government, through Trafikverket, road associations and forestry companies, private road owners and users form the main stakeholders in the gravel road ecosystem with different roles and needs [Q3]. The information needs of gravel road stakeholders are addressed by Abbas and Kans (2022) and Campos et al. (2020) for the Swedish case. Kans et al. (2021) propose a cloud-based ICT system that covers these information needs.

The annual traffic on gravel roads is less than 250 vehicles per day and consists of light and heavy truck loads, mainly transporting timber from the forests [Q4]. The main concern for road safety is loss of vision due to dust, and the most common accidents are cracked car windshields and body scratches. Severe fatal accidents do not generally occur on gravel roads. One respondent wrote that some drivers think they are Colin McRae and exceed speed limits, resulting in accidents [Q5]. Injuries and accidents are reported into an information system for data on injuries and accidents within the road transport system called Swedish Traffic Accident Data Acquisition (STRADA) [Q5]; see Web-1. Other countries, such as the United States of America, have reported many fatal accidents on unpaved roads (Dissanayake and Liu, 2010; Saeed *et al.*, 2021).

Maintenance planning is prioritised based on knowledge of the road condition and available resources. With limited resources, maintenance shifts towards corrective rather than prevention measures to maintain year-round carrying capacity, which is essential for commercial transportation, accessibility and ride comfort for those living and working in the countryside. Other measures include functionality-enhancing carrying capacity, including the wearing course and subbase, re-gravelling - wear-bearing measures, and dust suppression measures for dust control [Q6]. The annual average daily traffic is the most crucial parameter to determine if a gravel road requires paving. Roads with a traffic volume of fewer than 250 vehicles/day generally do not qualify for paving, and neither do forest roads. The social and economic benefits are also considered, i.e. comparing the maintenance and life cycle costs (LCC) of paved and unpaved roads [Q7].

For gravel road assessment, the standard "Bedömning av grusväglag TDOK 2014:0135" (Swedish Transport Agency, 2014) has been adopted for the following: Cross falls and roadsides, irregularities (potholes, corrugations), loose gravel and dust. During snow-thawing periods, the wearing course and subbase are evaluated for restricted heavy traffic to limit the damage to the road structure and ensure that accessibility for light vehicles is guaranteed. Most assessments are conducted through visual windscreen surveys [Q8] (see Web-2). The bearing capacity and accessibility are usually at their worst during snow thawing and periods with extreme rainfall, and potholes may also occur. During dry weather, dust is of considerable concern when the wearing course no longer binds together, resulting in unevenness, such as potholes and corrugations [Q9]. Poor crossfall prevents water from running off the road into the drainage. Inadequate drainage causes stormwater collection, impairing the load-bearing properties and leading to deficient subbase and ground frost [Q10].

At a strategic level, Trafikverket has divided the road network into six road types to describe the functionality and to achieve quality maintenance planning. Gravel roads are categorised into road type 4 - essential for business, road type 5 - vital to the countryside or road type 6 - other unpaved roads. Depending on the severity and extent of the damage, a gravel road is assigned the condition values 1, 2, 3 or 4. The four-level classification system implies that 1 is the best condition and 4 is the worst [Q11]. Most unpaved roads, including gravel roads, have a speed of 70 km/h or less, depending on their condition. For level four roads, the maximum speed could be as low as 20 km/h [Q12].

High traffic volume, heavy traffic and high vehicle speed influence the occurrence of gravel road defects; therefore, heavy trucks may be restricted during snow-thawing periods to limit damage [Q13]. Trafikverket is currently testing smartphone accelerometers to measure road roughness while documenting the condition with photos. Attempts have been made to measure unpaved roads with these special measuring vehicles used for annual measurement of the condition of the state-paved road network. Procurement is currently underway for a research and innovation project to provide digital information about the condition of the road directly from a sensor-equipped vehicle fleet [Q14].

All respondents had heard of participatory data collection for condition monitoring of assets and infrastructure [Q15]. A standardised objective measurement methodology for gravel road condition assessment at the national level should result in a more efficient and reliable measurement than a subjective assessment that depends on the assessor and their perception of the condition [Q16]. Trafikverket could consider participatory condition data collection on gravel roads in the future, provided it has been tested and verified as reliable and robust. They also needed to develop the ability to receive and manage all data efficiently [Q17].

Furthermore, participatory condition data collection would enhance maintenance planning and decision-making, including condition classification of gravel roads if properly managed [Q18]. The unpaved road condition data collected using a participatory approach would support gravel road assessment, maintenance planning and decision-making. The information includes irregularities (potholes, corrugation, loose gravel), crossfall and slope, state of the drainage, dustiness, road width (annual) and load-bearing capacity [Q19]. A data-driven alerting system based on participatory data collection, able to share the information with other stakeholders, could be attractive for Trafikverket, provided it is cost-effective [Q20].

4.2 The Zambia Case

RDA manages the operation and maintenance of the road network in Zambia. Zambia has about 50,000 km of the core road network; only about 20% is paved, and the rest is unpaved (earth or gravel road). The road network covers about 100,000 km, including gazetted and unclassified roads. The roads are classified as trunk, main, district, urban and feeder roads [Q1]. Almost 90% of the road network in Zambia consists of unpaved roads in both the urban and rural areas, providing access to schools and health facilities and between neighbouring urban centres and rural areas. They are the basis for social and economic development, especially in rural communities. Nearly all locally grown agricultural products on the market are transported on an unpaved road at one point before reaching the target market [Q2]. The key stakeholders in Zambia's unpaved road ecosystem include the government through RDA, local councils, communities and road users [Q3].

The traffic volume on unpaved roads can reach 300 vehicles per day (vpd) and consists mainly of light trucks with less than 10% heavy traffic. The traffic is high from June to August, when farmers harvest and sell their crops to business people, and from November to February, when farmers receive their agricultural inputs. In months of low agricultural activity, traffic can be less than 20 vpd [Q4]. Compared to paved roads, fatal traffic accidents are low on unpaved roads, usually caused by drivers' loss of vision due to dust and when the drivers attempt to swerve through potholes at higher speeds. Slippery roads during the rainy season also lead to accidents, and in dry seasons, loose stones can fly and shatter windshields, scratch car bodies, or even injure pedestrians. Careless driving by some drivers who drive at excessive speeds is another cause of some incidents. The respondent suggested contacting the Road Transport and Safety Agency (RTSA) for the latest accident statistics on unpaved roads; see Web-3 [Q5].

RDA conducts annual surveys to determine the condition of unpaved roads. The survey results form the basis for maintenance planning, subject to the availability of resources. Due to the competing need to maintain paved roads, the priority is towards paved roads instead. Unpaved roads only get some attention when they are almost impassable, especially in the rainy season [Q6]. The traffic volume is used to justify upgrading to paved standard, which should be over 300 vpd annually. An economic justification could be considered for reduced transportation costs in some areas with less traffic but poor materials for unpaved roads. There are isolated cases where some roads are paved due to political influence, even when they do not meet the traffic volume or the economic criteria [Q7].

Recent research in the southern African region indicates a reduction threshold for upgrading an unpaved road to a paved standard from greater than 300 vpd to between 100 and 200 vpd, influenced by environmental conditions on the road (National Steering Committee, 2019). Inspectors conduct annual visual surveys of unpaved roads and check the road condition. They check gravel thickness, camber (crossfall), longitudinal profile, surface defects, condition of the culverts and drainage [Q8]. The traffic volume on unpaved roads can reach 300 vehicles per day (vpd) and consists mainly of light trucks with less than 10% heavy traffic. The traffic is high from June to August, when farmers harvest and sell their crops to business people, and from November to February, when farmers receive their agricultural inputs. In months of low agricultural activity, traffic can be less than 20 vpd [Q4].

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Inspectors conduct annual visual surveys of unpaved roads and check the road condition. They check gravel thickness, camber (crossfall), longitudinal profile, surface defects, condition of the culverts and drainage [Q8]. The rate of deterioration of unpaved roads is highest during the rainy season, when the road surface is sometimes washed away by floods, making some areas inaccessible. The water that settles on the road surface accelerates the formation of potholes with every vehicle pass that dislodges the surface material and the water from the road surface. The roads are dustiest in the hot season, and the road surface is rougher because the binding material is lost as dust, leaving the surface stony [Q9]. Unpaved roads become very slippery in the rainy seasons, and roads usually flood due to poor drainage. The floods could wash away the road surface and bridges, making some areas inaccessible and cut off from the rest of the country [Q10].

Depending on the condition of the unpaved road, RDA classifies them into "good", "fair", and "poor". Most unpaved roads are in fair to poor condition, with a few in good condition [Q11]. The condition of the road determines driving speed on unpaved roads. For roads classified as good, driving speed could be up to 75 km/hr and as slow as 10 km/hr for poor conditions [Q12]. Heavy trucks and high traffic volume contribute to the fast deterioration of unpaved roads, especially during the rainy season. Higher speeds also accelerate the removal of road surface material as dust in the hot and dry seasons [Q13]. There has been some research in applying technology for assessing the condition of both paved and unpaved roads, but little progress has been made for unpaved roads. Progress has been made on paved roads and would be extended to unpaved roads with modifications to suit the environment. The possibilities of using smartphones have also been discussed and are being considered to measure road surface roughness. [Q14].

The respondent had heard of participatory data collection for condition monitoring of assets and infrastructure [Q15]. Participatory data collection would result in efficient road condition data collection, provided the data is collected reliably; otherwise, the data would be worthless and could lead to inaccurate maintenance decisions. Since most parts of the country have mobile internet connectivity and rural residents now own smartphones, finding participants would not be a challenge. However, ensuring data quality collection should be crucial [Q16]. Participatory data collection is worth exploring but requires further understanding of how it can be applied to the Zambian context.

Additionally, there is a need to invest in the necessary infrastructure to manage the data and staff trained to work with this type of data [Q17]. If implemented appropriately, maintenance planning and decision-making could be enhanced and would be a cost-effective approach to data collection [Q18]. Information regarding the road surface roughness, existing road defects, drainage and culvert condition, dustiness and vegetation growth near the road would be valuable for maintenance planning and decision-making [Q19]. Participatory data collection could provide valuable data and enhance the maintenance management of unpaved roads. However, the RDA must invest in the necessary infrastructure and personnel training to manage such a system. Zambia has not yet applied this alert system in road asset management. Therefore, it needs to be tested and validated, and the life cycle cost comparison is made for economic justification [Q20].

4.3 Comparison of Sweden and Zambia

A summary of the main findings of the Swedish and Zambian cases is found in Table 1.

Table 2. Comparison of Sweden and Zambia

S/N	Compared Attribute	Sweden	Zambia
1	Government-funded unpaved road mileage	About 95 000 km	Over 85 000 km
2	Traffic safety concern	Dust, loose gravel	Slippery road, dust
3	Condition assessment	Mainly visual survey	Visual survey
4	Condition classification	1, 2,3 and 4	Good, Fair, Poor
5	The threshold to consider paving	> 250 vpd	> 300 vpd
6	Season with the highest deterioration rate	Snow-thawing period	Rainy season
7	Plans of applying objective assessment methods	Testing smartphone accelerometers	Discussed and under consideration
8	Would they consider participatory data collection	Yes, after testing and validation	Yes, when supporting infrastructure in place
9	Benefits that would come with participatory data collection	Efficient and reliable measurement compared to a subjective assessment	Efficiency and reliability in data collection and improved maintenance planning

5. THE PROPOSED PARTICIPATORY CONDITION DATA COLLECTION APPROACH FOR UNPAVED ROAD MAINTENANCE

A participatory data collection approach for unpaved road maintenance empowers regular road users to collect condition data. The data is shared with the governing bodies, implying that assessors do not need to travel to the site to inspect road conditions and collect data. The process from data collection to decision support is described according to the OSA-CBM standard (Campos, 2009; Web-4). OSA-CBM is a standard architecture for moving information in a condition-based maintenance system and applies to unpaved road maintenance (Mbiyana *et al.*, 2021). OSA-CBM provides a suitable framework for data sharing between unpaved road maintenance stakeholders, including researchers in road infrastructure maintenance. The collected condition data is processed according to the steps of the OSA-CBM up to the maintenance decision support. The proposed participatory data collection approach for unpaved road maintenance, which comprises data collection and storage, data processing, manipulation, State detection, diagnosis and prognosis assessment and maintenance decision support, is shown in Figure 3. The approach procedure is briefly explained below.

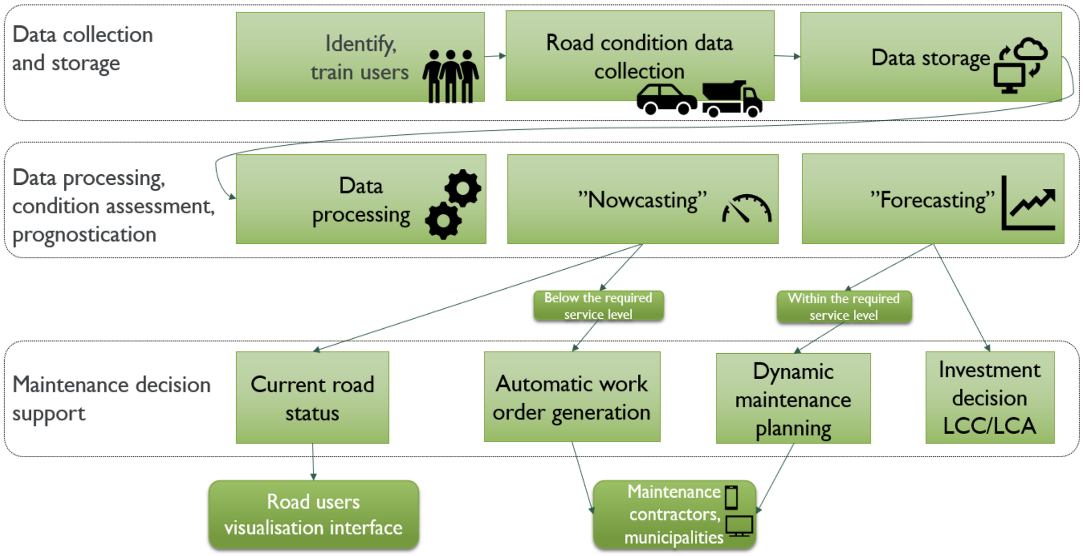

Figure 4. A proposed participatory data-driven approach for unpaved road condition monitoring

5.1 Unpaved road data collection and storage

Participants are identified and volunteer to collect unpaved road condition data as they go about their daily activities. These targeted participants include garbage collectors, postal service vehicles, public buses, unpaved road owners and rural residents. Volunteers are then trained to collect unpaved road condition data, for instance, using smartphones or standard-alone sensors fitted to their vehicles to ensure quality data collection. The measurement parameters must be identified during the training, the acquisition device calibrated, and the sensor placement position and attachment method determined. After the training, the volunteers can collect road condition data every time they drive on an unpaved road and share it with the governing bodies via the cloud. The data can include vibration data, videos and photos of the road. There are, however, several other factors that affect the quality of data collected, and these include:

- The properties sensor used, for instance, various models of smartphones, could have different accelerometers installed on them with differing properties like sensitivities and frequency range. Selecting an appropriate sensor and data acquisition method is vital in ensuring the quality of the data collected (Mbiyana *et al.*, 2021).
- The size, weight, length, and suspension system, including the driving speed, influence the vehicle's vertical vibration response induced by road surface irregularities (Wang *et al.*, 2020). Calibration of the vehicle response to the extent and severity of the road surface irregularities and the driving speed is vital.

For instance, Aleadelat et al. (2018) applied signal demodulation and wavelet transformation to reduce the effect of external factors (i.e., speed dependency, engine vibrations, and suspension system) on the measurement data. They found that the acquired smartphone accelerometer signals reflected the gravel road conditions. Ride quality is a primary factor in determining the deterioration of unpaved roads (Uys, 2011). Roadroid (Abu Daoud and Ksaibati, 2021; Forslöf and Jones, 2015) and Matlab mobile (Web-5), two examples of smartphone-based applications for collecting road condition data, have great potential for participatory data collection. They use built-in smartphone accelerometers with GPS to determine the roughness while photos and videos are taken to document the condition. The two mobile applications are available on the App Store and Google Play Store.

5.2 Data processing, condition assessment and prognostication

Data processing involves cleaning and analysing the data using numerous methods and techniques for enhanced data quality. Only when the data quality is acceptable can the analysis be performed to retrieve meaningful information (Campos et al., 2020). The data is then transformed into a format suitable for extracting features related to the condition of unpaved roads (Merkt, 2019). The current condition (Nowcast) of the unpaved road is then detected, and based on the set level of service, an automatic work order is generated for a detected anomaly to the maintenance contractor and municipalities. If no anomalies are detected, a prognostication of forecast future failures and their likely occurrence is done for dynamic maintenance planning, including investment decisions based on the life cycle cost (LCC) and life cycle analysis (LCA) (Mbiyana *et al.*, 2021). Performing a prognosis assessment requires the availability of current and historical data and the relevant statistical and signal processing tools to forecast the maintenance needs and the remaining useful life (Campos, Sharma et al., 2020; Mbiyana et al., 2021). Road users can view the current road state using their smartphones and decide on the appropriate route using a road interface app of the current unpaved road condition. The lack of relevant historical road condition data has been identified as one of the challenges in applying data-driven approaches for unpaved road maintenance decision support and management due to the subjective method predominantly used for condition assessment (Mbiyana *et al.*, 2022).

5.3 Unpaved road maintenance decision support

Based on the condition assessment and prognostication results integrated with other sources of information, such as resource availability, a decision is made on the action to take. An unpaved road management system is required to implement a participatory data-driven approach for monitoring the unpaved road condition, leading to effective maintenance planning and decision-making (Rashedi *et al.*, 2018). An unpaved road management system would also serve as a repository for historical data, which would help address the lack of historical condition data in unpaved road maintenance.

6. CONCLUSION AND RECOMMENDATION

Unpaved roads deteriorate faster than paved roads, and their mode of deterioration and working environment also differ, necessitating frequent data collection to determine the road condition and for prompt maintenance decisions. However, data collection for condition monitoring requires resources, and the inspectors must travel to various sites to collect the data. Therefore, the condition assessment on paved roads cannot be applied directly to unpaved roads. Upgrading many of these roads to a paved standard is not cost-effective for most road agencies from a life cycle point of view. Therefore, it is imperative to have an efficient and effective approach for collecting condition data as an extensive network of essential unpaved earth and gravel roads will continue for the foreseeable future, both in Sweden and Zambia. Ensuring such roads are designed cost-effectively and maintained appropriately and promptly is critical to guarantee driving comfort and safety. According to the case study, the maintenance practices in Sweden and Zambia differ. However, subjective visual assessment of the unpaved road condition is predominant, and data-driven objective methods are rarely applied.

Participatory data collection for unpaved roads offers an efficient and effective alternative for collecting unpaved road condition data for both countries and achieving broader coverage. It is based on OSA-CBM and allows road users to be part of the maintenance process. Data quality affects the outcome of data processing and analysis. Therefore, data handling, especially at the acquisition stage, is critical. The participants' privacy must be guaranteed, especially when using personal smartphones for data collection. The proposed approach should be user-friendly to be effective and for maximum utilisation by allowing participants to be part of the development process and to conduct training and workshops occasionally. The case study also reveals the willingness of the governing bodies to incorporate objective methods, including participatory data collection, for collecting data on unpaved road conditions. A holistic maintenance approach would reduce maintenance costs from data collection and road condition assessment. The trickle-down effect is improved unpaved road maintenance planning and decision-making, resulting in improved road reliability.

The information from the maintenance decision support allows the road authorities, including maintenance contractors, road owners and municipalities, to develop an optimum maintenance plan and improve resource allocation and productivity. Unpaved roads that are adequately maintained increase road safety, minimise road users' operation and maintenance costs, and reduce delays caused by road failures. The road users' visualisation interface provides a platform that depicts the road's current condition, and the users can plan their routes based on an informed position of the condition. The presented approach is a foundation for developing a participatory data collection approach to achieve efficient and effective unpaved road maintenance practices. Therefore, smaller agencies and road owners lacking resources to implement costly innovative ideas could implement a participatory data-driven approach for unpaved road condition monitoring to manage unpaved roads in the short term.

Future works will explore the practical implementation of a participatory data-driven approach for unpaved road condition monitoring and data collection using smartphones and an Integrated Circuit Piezoelectric (ICP) accelerometer widely used in various industries to measure vibration and acceleration due to its sensitivity, broad frequency range, and ease of installation. We recommend that Trafikverket and the RDA in Zambia investigate the possibility of implementing a participatory data-driven approach for unpaved road condition monitoring and data collection.

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APPENDIX

List of the interview questions

Question Number	Interview Questions
Overall questions regarding the unpaved road network and its maintenance	
1	What is the current unpaved road mileage throughout the country? Compared with the paved mileage. How are they distributed in the country?
2	What role do unpaved roads play?
3	Who are the main stakeholders in the unpaved road ecosystem? If possible, outline the primary needs of each stakeholder.
4	What is the annual average daily traffic on unpaved roads, and what is the traffic composition?
5	What is the current traffic safety on unpaved roads? What accidents are recorded annually, and what is their extent? What is the likely primary cause of these accidents?
6	How do you plan for maintenance, and how do you prioritise the maintenance, considering the scarcity of resources?
7	Has the option of paving the unpaved roads been considered?
Questions regarding condition assessment and monitoring of unpaved roads	
8	How is the condition of unpaved roads assessed, and what defects/faults are assessed?
9	What is your opinion about the quality of unpaved roads in the seasons of the year? In which season is the deterioration rate highest?
10	What is the major defect/fault during the season with the highest deterioration rate? (Defects likely such as unevenness, potholes, wash boarding, dusting and road firmness; see Q6)
11	Do you have any form of road condition classification for unpaved roads? If yes, how are unpaved roads classified with regard to their condition?
12	What are the maximum speeds on unpaved roads for each condition class?
13	How do traffic factors (vehicle type, speed, and volume) affect unpaved roads?
14	Have you applied objective data-driven methods (sensor technology) to assess the condition of unpaved roads? What is hindering you from exploiting such technological advances for condition monitoring if you have not?
Participatory data collection and sensing	
15	Have you heard of participatory data collection and sensing for condition monitoring of assets and infrastructure?
16	What advantages and disadvantages would participatory data collection and sensing for condition monitoring offer compared to the current practices?
17	Is it an option you might exploit in the future? What are the hindrances to your organisation's consideration for a participatory collection of unpaved road condition data?
18	Would participatory condition data collection enhance maintenance planning and decision-making, including improving unpaved road condition classification in your organisation?
19	What kind of information would you need to collect if you consider participatory data collection for unpaved road assessment, maintenance planning and decision-making?
20	What is your opinion about having a data-driven alert system in your unpaved road maintenance system based on participatory data collection and being able to communicate this information with the other stakeholders? What do you think of such a future system?