Influence of GIS on sustainable pavement maintenance: a comparative review

B U Ngene, D E Bassey*, A A Busari, G O Bamigboye and A T Nworgu

Department of Civil Engineering, Covenant University, Ota, Ogun State, Nigeria
*Corresponding author: bassey.daniel@gmail.com

Abstract. Road transportation remains dominant in passenger and freight movements across Africa. Yet, a majority of the countries in Africa do not perform proactively in ensuring the sustainability of highway infrastructure. This research reviews recent literature in recognizing the state-of-the-practice on the application of GIS-based techniques in sustainable pavement maintenance, hence promoting a systematic approach for highway maintenance management. Furthermore, it compares contemporary maintenance practices in the five major African regions to highlight the differences and similarities. Most countries have since implemented institutional reforms such as the provision of road funds and agencies, thereby making substantial improvements on road maintenance. However, several challenges, including inadequate financing, lack of technical expertise, poor administration, and lack of continuous research and development still hinder sustainable road maintenance in Africa. Hence, most African countries still depend solely on budget financing while adopting delayed and reactive approaches to highway maintenance activities. The study revealed that sustainable methods of pavement maintenance have neither been incorporated in policy nor practices involving highway pavement management in most African nations. And as such, it encourages respective road agencies to integrate GIS-based techniques into road maintenance management at all functional levels to promote sustainability.

1. Introduction
The serviceability of any nation’s roadway network plays a key role in its social and economic advancement since passenger and freight mobility, and land accessibility are major aspects [1, 2]. Gujba et al. [3] reported that averagely, road transport in Africa controls about 90% and 80% of passenger and freight movements, respectively. The lack of modal diversity in transportation has resulted in the over-dependence on roads for transportation and consequently, increased carbon emissions, noise pollution, traffic congestion, and ultimately, stress-induced pavement failures. Most African Nations inherited roads initially developed for colonial domination and military ascendancy [4]. An adequately integrated and functional road network system aids in accelerating the fiscal growth of any nation, via tourism, trade, and other feasible developments [5]. Due to limited funding, road networks, especially in the African continent, were only developed and maintained to certain extents. As such, road maintenance practices remain inadequate in many African countries [4]. In response to the United Nations, sustainable development goal 11 for the development of sustainable cities and communities, sustainability in pavement maintenance has gained attention in recent years. To avert failures and guarantee level of service, road infrastructure requires constant Maintenance and Rehabilitation (M and R). In many cases, road management agencies are guilty of allowing roadways to
fall into severe conditions before taking the required actions. Nevertheless, proactive preservation actions endorse management systems while the roadways are still in proper condition [6]. As such, highway management agencies search for methods to improve pavement preservation in a quality and cost-efficient manner, such as the advanced Pavement Management Systems (PMS) [7]. PMS institutes organizational and computational programs for pavement assessment, detecting the present conditions, recognizing failure rates, and evaluating several maintenance alternatives taking contemporary and impending costs into account [8].

Several computer programs have been developed employing vital functions of modern PMS alongside spatial data from Geographic Information Systems (GIS) [9]. PAVER™ is the most commonly used PMS software. It conducts series of analyses using pavement condition index (PCI) data with values between zero (failed condition) and 100 (excellent condition) for a precise description of pavement conditions and prediction of contemporary and future M and R requirements [10]. Recently, software has utilized GIS/GPS technology and state-of-the-art graphics processing in simplifying pavement inspection with the use of mobile devices by permitting users to identify device locations on geo-referenced road maps displayed for prompt input of pavement distress information [11]. This paper reviews modern practices on pavement maintenance management systems, highlighting common pavement distresses, M and R categories, and GIS-based methods for sustainable pavement maintenance it further discusses the different M and R practices in the five regions of Africa, taking the most populous country within each region as a case study. The focus is on comparing and contrasting the different contemporary M and R perspectives in the regions.

2. Components of Road Maintenance

2.1 Pavement distresses

Distresses may start during construction and proliferate over time. Poor construction methods most certainly guarantee the poor performance of pavements. Distress may occur in flexible pavements due to reasons like seasonal variations, recurring traffic loadings, poor drainage, aging, or combinations [12]. Some common distresses in asphaltic pavements include rutting, fatigue cracking, roughness, thermal cracking, shoving, bleeding, raveling, and reflection cracking [13].

2.2 M and R categories

M and R involves practices for preserving the performance of road structures. It is achieved by correcting pavement distresses that develop over time while considering durability and environmental sustainability [6]. M and R operations in Nigeria are categorized in Table 1.

Table 1. Road maintenance categories and description.

| Category       | Description                                                                 |
|----------------|----------------------------------------------------------------------------|
| Routine        | Regularly required on roads of all functional classes. Costs are considered fixed in maintenance budgets, activities include lane marking drainage clearing, culverts and bridge maintenance, turf cutting, amongst others. |
| Recurrent      | Conducted at specified intervals within the year. Maintenance operation frequency is reliant on climatic and topographic conditions, and the traffic volume conditions. Activities include repair of cracks, potholes, and other road distresses and releveling or grading for unpaved roads. |
| Periodic       | This comprises major rehabilitation of failed sections along roads. The frequency of occurrence is usually very low as it is performed only when the need arises. Activities include shoulder re-graveling and carriageway resurfacing, amongst others. |
| Emergency / Special Repairs | Undertaken only in extreme unexpected situations such as momentous landslides, tectonic or seismic movements across roadways, culvert or bridge failures, and pavement explosion due to terrorism amongst other tragedies. |
3. **Pavement Maintenance Management Systems (PMMS)**

PMMS integrates coherent and systematic activities aimed at the effective management and maintenance of road pavements [14]. Benefits of PMMS include: the development of digitized databases for storage of pavement data; encouraging the practice of regular pavement monitoring for collection of pavement distress data; making optimized lists to aid in selecting maintenance and rehabilitation works based on necessity and resources; predicting impending distresses and providing documentation of the required intervention to support requests for project funding.

3.1. **Assessment of Current Pavement Conditions**

The process begins with taking an inventory of the road network based on visual inspection of the surface as a vehicle with the acquisition system pre-installed on travels along the pavement. The user records the data on spreadsheets based on the objectives of the inspection [15]. A spatial database is developed with collected data representing the road network. ArcGIS® ModelBuilder™ is then used in developing digitized models. Data collected represent locations along the roads and are geo-referenced using the linear referencing system (LRS) during data import. After the database population, analysis is done using codes written in Python® to assess the current state of the pavement expressed in PCI.

3.2. **Prediction of Future Pavement conditions**

When predicting pavement future PCIs, material quality, climatic conditions, storm and subsurface hydrology, traffic volume, and maintenance policies are governing factors which may become variable. As such, PMS adopts predictive models in deducing future pavement conditions based on contemporary data. Probabilistic and deterministic models such as the Markov chains and AASHTO methods, respectively have been utilized in past studies [16, 17].

3.3. **Role of GIS in PMMS**

Transportation systems associated data are perfect fits for GIS analysis because of the spatial distribution of features. Hence, GIS has been used in increasing the efficiency of transport planning and M and R systems significantly in terms of cost and time efficiency, and decision making.

3.3.1. **Application of PAVERTM and ArcGIS® Programs.** The PAVERTM software was developed to aid PMMS activities. Pavement condition ratings are expressed in PCI after parallel assessments of available distress intensities and extents. Figure 1 shows PCI range attainable from PAVERTM 6.5.7.

![Figure 1](image_url)

**Figure 1.** [a] Road network map showing road sections within Abuja, Nigeria with varying PCIs [b] PCI range values (Source: [10])

Characteristically, a scale of seven distinct color-coded classes is used to categorize different pavement conditions. PAVERTM 7.0 receives data collected during initial inspection and assesses using 19 levels of distress, making it a highly thorough PMS software [10]. Output reports from PAVERTM provide summarized charts and tables showing statistics of the selected pavement network such as total area,
number of branches and segments, average PCI of segments, and area-weighted PCI across pavements. The PAVERTM software output data is compatible with most GIS programs. ArcGIS® was used in studies by Bazlamit et al. [8] and Wolters et al. [9] to further display results with the use of color-coded maps. PAVERTM output file is imported into ArcGIS as a shapefile on a new layer for plotting.

4. Comparison of Contemporary Highway M and R Practices in Africa

4.1 Highway M and R in Western Africa: Nigeria situation

Nigeria, with a population of over 200 million people, highest in Africa, has the largest and second-largest road network in West Africa and Sub-Saharan Africa, respectively. The Nigerian road network is currently estimated at 194,000 km [18]; however, Nigeria’s road sector performance has been unsatisfactory, thus negatively affecting socio-economic growth. Continuous funding has been directed towards the development of roads; however, the increasing population and traffic volumes keep the roads in a critical state [4].

The Federal roads maintenance agency (FERMA) is saddled with the duty of inspecting and maintaining all Federal roads within the country. They manage only 17% of the nation’s road network while the state and local governments are responsible for the state (16%) and local (67%) roads, respectively [19]. The deterioration rates have outpaced the maintenance rates as a result of the decapacitated levels of finance and technical expertise for M and R efficiency [20].

A few studies have assessed PMS in Nigeria. Owolabi et al. [21] developed an assessment model for the performance of the Lagos – Ibadan expressway via pavement condition score (PCS) and international roughness index (IRI) data collected from the evaluation unit of the Federal Ministry of Works. Also, Owolabi and Abiola [22] established a priority index (PI) model for the assessment and forecast of pavement conditions. A linear relationship between equivalent standard axle loading (ESAL), IRI, PCS, and PI, under many forms of pavement distresses, was developed, while the prediction of future pavement conditions was done via artificial neural network and multiple linear regression [22]. Despite endorsements from researches, road pavement maintenance in Nigeria is still done reactively rather than on a proactive basis. As such, the need for a reform of the currently ineffective but adopted M and R schemes in Nigeria is critical. In General, the M and R issue in Nigeria can be addressed through proper funding, research, and development. These can reform the approach of M and R contracting at federal, state, and local government levels to a performance-based approach via public-private participation to ensure cost-efficiency.

4.2 Highway M and R in Eastern Africa: Ethiopia situation

Ethiopia, populated with over 112 million people, second-highest in Africa, and generally categorized as an underdeveloped country has in the past decade increased the reach of its road network by over 100% as a result of its modernized PMS approach to highway M and R. The Ethiopian road network estimated at 6,400 km as of 1951 grew to over 46,000 km in 2010, and about 85,966 km in 2015 [4]. The earlier lack of comprehensive PMS M and R techniques resulted in the accrual of the backlog of road maintenance. Nonetheless, the reform of M and R management initiatives, including ownership, management, financing, and responsibility is progressively leading Ethiopia out of the shadows of poor roadway networks [4].

The Ethiopian Road Transport Authority (RTA) with the aid of the Ethiopian government is responsible for the regulations and controls leading to the road network growth in Ethiopia. RTA was enacted in 1967 to oversee roads and road-using vehicle-related matters, as such, RTA has since taken maintenance as key to achieving its goals [4]. Since road management is continually hindered by funding, the road fund was established in Ethiopia in 1997, with significant consideration towards resolving the maintenance funding issues. This fund is based on a charge-for-service principle. To great extents, the M and R reform has been encouraged. As such, Ethiopia was recently classified as satisfactory performers in terms of M and R. Generally, the M and R culture in Ethiopia has greatly grown in the last few years due to appropriacy in funding via the road fund model and the adoption of PMS in the M and R sector [4].
4.3 Highway M and R in Northern Africa: Egypt situation

Egypt is the third most populous African nation with over 100 million people. Here, road M and R is said to be neglected, as it accounts for only 0.15% of the country’s GDP. This is minor compared to Ecuador, Morocco, and Ukraine with 0.23, 0.24%, and 0.45%, respectively. This negligence has been consequential in increased road accident rates which in turn accounts for 1.5% GDP loss [4]. In 2001, the government increased the road funds to improve the transportation sector. However, about 75% of the roads still require maintenance; as approximately 700 of the 1,706 bridges in Egypt were in critical states due to poor M and R in 2009 [4].

In addressing the situation, the General Authority of Roads, Bridges, and Land Transport (GARBLT) was set up to oversee the construction and maintenance of roads in the country. GARBLT recently commenced the bridge maintenance and repair program. However, the program has yielded low success rates as a result of inadequacy in human resources in terms of technical expertise, and equipment for adequate inspection and assessment of bridges. Generally, the state of road M and R in Egypt is still a quandary, and requires rehabilitation rather than maintenance [4]. GARBLT’s major issue has been funding, as such an initiative was introduced to generate funds via tolling, advertising, and issuance of fines amongst others.

4.4 Highway M and R in Central Africa: Democratic Republic of Congo (DRC) situation

The DRC, with over 86 million people, is ranked 4th most populous in Africa. DRC’s transport infrastructure system is currently one of the most dilapidated across the globe [23]. The DRC road network spans a total of 171,250 km, of which only 2,250 km are paved [24]. Traveling to Kinshasa, the capital, by road is impossible since most of the provincial capitals are not linked. Another major bottleneck in road transportation across the country is the poor state of bridges used in crossing several small rivers. The DRC possesses an extensive inland river network; however, water transport is still hampered by long wait periods at ports resulting from poor infrastructure, high rates of silting, and uneven governance [23]. The Roads Authority of the DRC is responsible for the management of road maintenance and construction operations of all national and regional roads. At the same time, the Direction of Agricultural Roads and Services maintains the secondary and local roads. However, key infrastructure M and R projects are currently being done by international agencies such as the World Bank (3,500 km), European Union (2,000 km), the UK Department for International Development (1,300 km), KfW Development Bank (280 km), and the African Development Bank (150 km) [24].

Currently, the populace suffers from insufficient roadways and are obliged to resort to air transportation for passenger and freight movements. Only a few roadways in the DRC: Kinshasa to Port of Matadi, and Likasi – Kipushi – Lubumbashi in Southern Katanga have remained in good condition [24]. However, since 2005, the United Nations Joint Logistics Centre (UNJLC) has collected and disseminated road condition data in the DRC using the GIS Working Group and its various partners. These data are registered in geo-databases hosted by the UNJLC. They are steadily updated via remote sensing methods from the Belgian University of Louvain [24] in attempts to resuscitate the country’s road M and R activities.

4.5. Highway M and R in Southern Africa: South Africa (SA) situation

SA, with over 68 million people, is the sixth most populous country in Africa. SA road network spans about 746,978 km, the longest in Africa, 10th longest globally, and 18th longest in terms of paved roads worldwide (153,719 km) [4]. South-Africa is foremost economically in the continent and as such perform better in road M and R compared to other African Nations. However, about 38% of its roadways are in fair to poor conditions [25]. The South African National Roads Agency SOC Limited (SANRAL) handles road M and R in SA. SANRAL accounts for 92% of the national roadway network, of which 19% are tolled and the remaining, toll-free. The 8% remaining from the total road network are privately managed, hence, tolled. The SANRAL regulated these private bodies based on thirty-year concession contracts [4].
SANRAL alongside Namibia can be categorized as top road M and R performers in Africa even though SA has a road M and R funding backlog between 80 and 149 billion Rand [4]. It has adopted efficient PMS-based routine, periodic and emergency maintenance strategies. Municipal roads are the only fraction not managed adequately due to poor data collection (only 4% of PCI data available), and consequently, poor coordination of municipal M and R responsibilities. However, the performance-based method for contracting M and R works has significantly been instrumental in the success attained in SA [4].

5. Discussion and Recommendations for Road M and R in Africa
In general, M and R activities in most African countries are very similar; however, the methods vary. Nonetheless, the importance of road M and R cannot be overemphasized due to its massive influence on regional amalgamation, economic advancement through efficient public administration and security, and social development. Furthermore, M and R prolongs the serviceability and safety of roadways, thereby minimizing internal and external costs of road usage. However, delay in M and R can be equivalent to its reconstruction as it leads to high direct and indirect costs.

Compared to other African countries, Ethiopia has a working road funding model autonomous of governmental input. However, SA and Namibia also record tremendous success in this regard while other Nations remain reliant on governmental funds. These funds are often constrained by the country’s development needs. As such, road M and R always receive the least priority. Moving forward, the development of road funding models suiting specific national and cultural requirements is essential, especially in nations with vast populations such as Nigeria. Figure 2 illustrates the comparison between the countries discussed.

Concentrating on the technical issues related to M and R in Africa, it is clear that the issue of deficiency of data is encountered in all regions. It is therefore of utmost necessity that all African countries adopt GIS-based PMS methods in meeting road M and R requirements effectively. The development of spatial inter-state databases can further help in reducing road construction and M and R costs [4].

![Figure 2](image.png)

**Figure 2.** Comparison of M and R practice in selected African countries

6. Conclusions
This study reviews recent literature in recognizing the state-of-the-practice on the application of GIS-based techniques in sustainable PMMS, hence promoting a systematic approach for highway M and R operations. Additionally, it compares current M and R practices in the five major African regions. The study reveals that compared to individual nation’s economic capacity, road M and R efforts are relatively high, however, compared with sustainable standards adopted in developed countries across the globe, these efforts lack significance. In the aspect of road ownership and establishment of management
agencies and responsibilities, most African nations have performed well. However, the financing, technicality, and research and development aspects remain deficient as a majority still depend solely on budget financing, while adopting delayed reactive approaches to highway M and R activities. As much as the road agencies may want to perform, the issue of financing has always been a hindrance.

In conclusion, there is a great necessity for African countries to:

i. Seek alternative sources for M and R funds,
ii. Integrate GIS-based PMS into M and R works at all functional levels,
iii. Consider the performance-based contracting approach for M and R,
iv. Invest in other modes of transportation such as railways and waterways to reduce pressure on roadways.

Acknowledgements
The authors wish to appreciate the management of Covenant University competently led by the Chancellor, Dr. David O. Oyedepo for the platform made available for this research and the sponsorship.

References
[1] A. M. G. Ribeiro, S. D. Capitão, and R. G. Correia, “Deciding on maintenance of small municipal roads based on GIS simplified procedures,” Case Stud. Transp. Policy, vol. 7, no. 2, pp. 330–337, Jun. 2019.
[2] A. N. Ede, “Cumulative Damage Effects of Truck Overloads on Nigerian Road Pavement,” Int. J. Civ. Environ. Eng., vol. 14, no. 01, pp. 21–26, 2014.
[3] H. Gujba, Y. Mulugetta, and A. Azapagic, “Passenger transport in Nigeria: Environmental and economic analysis with policy recommendations,” Energy Policy, vol. 55, pp. 353–361, Apr. 2013.
[4] H. M. Mostafa, “Road Maintenance in Africa: Approaches and Perspectives,” in 4th International conference on Energy Materials and Environmental Engineering (ICEMEE), E3S Web of Conferences, 01005, 2018, vol. 38.
[5] S. A. Ojo, J. O. Olusina, B. U. Ngene, A. A. Busari, J. Adediran, and A. Eletu, “Assessment of road infrastructure using remote sensing and GIS methodology for monitoring the condition of paved and unpaved roads,” in 1st International Conference on Sustainable Infrastructural Development, IOP Conf. Series: Materials Science and Engineering, 012099, 2019, vol. 640.
[6] Y. Zhang and J. P. Mohsen, “A Project-Based Sustainability Rating Tool for Pavement Maintenance,” Engineering, vol. 4, no. 2, pp. 200–208, Apr. 2018.
[7] P. C. Anastasopoulos, R. J. G. M. Florax, S. Labi, and M. G. Karlaftis, “Contracting in highway maintenance and rehabilitation: Are spatial effects important?,” Transp. Res. Part A Policy Pract., vol. 44, no. 3, pp. 136–146, Mar. 2010.
[8] S. M. Bazlamit, H. S. Ahmad, and T. I. Al-Suleiman, “Pavement Maintenance Applications Using Geographic Information Systems,” in Procedia Engineering, 2017, vol. 182, pp. 83–90.
[9] A. Wolters, K. Zimmerman, K. Schattler, and A. Rietgraf, “Implementing Pavement Management Systems for Local Agencies: State-of-the-Art/State-of-the-Practice,” Illinois, 2011.
[10] R. R. A. Almuhanna, H. A. Ewadh, and S. J. M. Alasadi, “Using PAVER 6.5.7 and GIS program for pavement maintenance management for selected roads in Kerbala city,” Case Stud. Constr. Mater., vol. 8, pp. 323–332, Jun. 2018.
[11] PAVER™, “PAVER - Pavement Management Software,” 2019. [Online]. Available: http://www.paver.colostate.edu/. [Accessed: 11-Jan-2020].
[12] A. Chen, Y. Zhao, P. Li, Y. Li, M. Mohammed, and P. Guo, “Crack propagation prediction of
asphalt pavement after maintenance as a function of initial cracks distribution,” Constr. Build. Mater., vol. 231, p. 117157, Jan. 2020.

[13] T. F. Fwa, The Handbook of Highway Engineering. Boca Raton, FL: CRC Press Taylor & Francis Group, 2006.

[14] J. Farhan and T. F. Fwa, “Pavement maintenance prioritization using analytic hierarchy process,” Transp. Res. Rec., no. 2093, pp. 12–24, 2009.

[15] L. Picado-Santos et al., “Pavement management system for Lisbon,” Proc. Inst. Civ. Eng. Munic. Eng., vol. 157, no. 3, pp. 157–165, 2004.

[16] P. Di Mascio and L. Moretti, “Implementation of a pavement management system for maintenance and rehabilitation of airport surfaces,” Case Stud. Constr. Mater., vol. 11, Dec. 2019.

[17] M. K. Jha and J. Abdullah, “A Markovian approach for optimizing highway life-cycle with genetic algorithms by considering maintenance of roadside appurtenances,” Met. Finish., vol. 104, no. 6, pp. 404–419, Jun. 2006.

[18] Federal Road Safety Commission, “Road Accident Statistics in Nigeria,” 2013.

[19] Central Bank of Nigeria, “Highway Maintenance in Nigeria: Lessons from other countries,” 2013.

[20] Federal Ministry of Works Nigeria, “Compendium report on road infrastructural and related development in Nigeria- An inventors manual,” 2013.

[21] A. O. Owolabi, O. M. Sadiq, and O. S. Abiola, “Development of Performance Models for a Typical Flexible Road Pavement in Nigeria,” Int. J. Traffic Transp. Eng., vol. 2, no. 3, pp. 178–184, 2012.

[22] A. O. Owolabi and O. S. Abiola, “Development of Priority Index Assessment Model for Road Pavements in Nigeria,” in 8th International Conference on Managing Pavement Assets, 2011, pp. 1–13.

[23] World Bank Group., “Transport, Economic Growth, and Deforestation in the Democratic Republic of Congo: A Spatial Analysis,” 2016.

[24] United Nations Joint Logistics Centre (UNJLC), “DRC Snapshot: Roads in the DRC,” 2017.

[25] D. Jones, P. Paige-Green, and E. Sadzik, “Development of Guidelines for Unsealed Road Assessment,” Transp. Res. Rec. J. Transp. Res. Board, vol. 1819, no. 1, pp. 287–296, Jan. 2003.