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ORIGINAL

Sustainable development of road tourism: Model-based forecast of future trends

Desarrollo sostenible del turismo por carretera: previsión basada en modelos de las tendencias futuras

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ABSTRACT

Objective: road tourism plays a crucial role in sustainable regional development, involving intelligent route planning to balance tourist demand, environmental sustainability, and infrastructure capacity. Traditional methods often fail to capture the dynamic nature of visitor preferences, which are influenced by the previous behaviors, traffic congestion, and environmental factors. The research aims to address these limits by forecasting future trends in sustainable road tourism using a superior predictive model.
Method: to tackle the challenges, this research proposes a Bidirectional Gated Recurrent Unit fused Dynamic Random Forest (Bi-GRUForest) model. The Bi- model integrates a Bi-GRU for tourist route recommendation and a Dynamic Random Forest (DRF) network to capture travel patterns, with a temporal attention mechanism incorporated to prioritize key travel intentions. Multi-source data, comprising environmental data, road infrastructure, and tourist movement patterns, are gathered and preprocessed utilizing techniques like outlier removal, missing value handling, and normalization to ensure consistency, reliability, and accuracy. Real-time data on road conditions, weather updates are integrated to promote eco-friendly travel choices.
Results: experimental results demonstrate that Bi-GRUForest outperforms existing models in forecasting travel trends, optimizing road network efficiency, and supporting environmentally responsible tourism development. The model achieves a recall of 90,2 %, precision of 89,5 %, F1-score of 87,9 %, and lower error rates with MAE of 600,01, MAPE of 15,10, and RMSE of 700,01.
Conclusions: the research provides valuable insights for policymakers, transportation planners, and tourism stakeholders, improving route prediction accuracy, reducing carbon emissions, and alleviating traffic congestion, contributing to the development of more sustainable road tourism and practices.

Keywords: Road Tourism; Future Trends; Bidirectional Gated Recurrent Unit-fused Dynamic Random Forest (Bi-GRUForest); Route Recommendations; Travel Trajectories.

RESUMEN

Objetivo: el turismo por carretera desempeña un papel crucial en el desarrollo regional sostenible, lo que implica una planificación inteligente de rutas para equilibrar la demanda turística, la sostenibilidad medioambiental y la capacidad de infraestructura. Los métodos tradicionales a menudo no logran captar la naturaleza dinámica de las preferencias de los visitantes, que están influenciadas por los comportamientos anteriores, la congestión del tráfico y los factores ambientales. La investigación pretende abordar estos límites mediante la previsión de tendencias futuras en el turismo sostenible por carretera utilizando un modelo predictivo superior.

Método: para abordar los desafíos, esta investigación propone un modelo de bosque aleatorio dinámico bidireccional cerrado con unidad recurrente fusionada (Bi-GRUForest). El modelo Bi- integra un Bi-GRU para la recomendación de rutas turísticas y una red de bosque aleatorio dinámico (DRF) para capturar patrones de viaje, con un mecanismo de atención temporal incorporado para priorizar las intenciones de viaje clave. Los datos de múltiples fuentes, que comprenden datos ambientales, infraestructura vial y patrones de movimiento turístico, se recopily preprocesutilizando técnicas como la eliminación de outlier, manejo de valor perdido y normalización para asegurar la consistencia, fiabilidad y precisión. Los datos en tiempo real sobre las condiciones de las carreteras y las actualizaciones meteorológicas se integran para promover opciones de viaje respetucon el medio ambiente.
Resultados: los resultados experimentales demuestran que Bi-GRUForest supera los modelos existentes en la previsión de las tendencias de viaje, la optimización de la eficiencia de la red de carreteras, y el apoyo al desarrollo del turismo ambientalmente responsable. El modelo logra un recuerdo de 90,2 %, una precisión de 89,5 %, un F1-score de 87,9 %, y menores tasas de error con MAE de 600,01, MAPE de 15,10, y RMSE de 700,01.
Conclusiones: la investigación proporciona información valiosa para los formuladores de políticas, los planificadores de transporte y las partes interesadas en el turismo, mejorando la precisión de la predicción de rutas, reduciendo las emisiones de carbono y alivila congestión del tráfico, contribuyendo al desarrollo de prácticas y turismo por carretera más sostenibles.

Palabras clave: Turismo por Carretera; Tendencias Futuras; Bidirecgated Recurrentes Unit-fused Dynamic Random Forest (Bi-GRUForest); Recomendaciones de Ruta; Trayecto de Viaje.

INTRODUCTION

Road tourism extensively contributes to regional economic growth and cultural exchange, contributing traveler's flexibility and entrance to diverse destinations. As concerns around environmental sustainability grow, there is rising prominence on aligning tourism development with eco-friendly practices. Sustainable road tourism engages managing infrastructure use, minimizing environmental impact, and addressing the changing preferences of travelers. A factor such as traffic congestion, carbon emissions, and resource availability plays an essential role in shaping tourism patterns. With the increase of tourism throughout the globe, the demand for sustainable practices for road tourism is becoming increasingly pertinent. Road tourism consists of a journey made by using a car, bus, or motorcycle over a long distance.[1,2,3] This journey is considered a vital force in the economic production and cultural exchange between nations. On the isolated side, it tends to develop quickly, creating challenges regarding its effect on the environmental impact, resources consumption, and the welfare of local communities.[4,5,6] The carbon footprint of transport particularly from vehicles utilizing fossil fuels, is the primarily concerns. Such emissions directly cause climate change and air pollution which can harm damage to both urban and nonurban destinations that attract tourists and residents alike.[7] Furthermore, road tourism can sometimes bring about over-tourism in some destinations by over-exhausting the natural resources, infrastructure, and cultures of the local communities in the region.[8] It could mean promoting electric vehicles and hybrid buses in these environments during tours to instill responsible tourist behavior leading to waste reduction and respect for the environment, ensuring the sustainability of similar tourist experiences.[9,10,11,12,13] Likely benefit-based sustainable approaches should integrate some of these tourism policy developments, which include green routes or eco-certification for tourism operators, all essentially aiding that tourism exists in harmony with protecting environment. Sustainable road tourism attempts to create an economic income without sacrificing environmental conservation and respect for culture. Road tourism is basically all travel undertaken by road with an extended span on cars, buses, or motorcycles.[14] It is the backbone of the world tourism industry that brings together remote areas, facilitates cultural exchanges, and creates wealth in local economies. Road tourism is promoted, especially in nature and adventure tourism, due to its flexibility, accessibility, and possibility of contact with less-developed peripheral areas. Among travelers, it is quite appealing as it involves for the possibility for complete immersion in the travel experience, benefiting local enterprises by providing jobs and enabling tourist to connect closely with their destinations.[15,16,17,18,19] Additionally, road tourism can cause disruptions to local communities, affecting the way of life and cultural integrity, as well as the lack of sustainable infrastructure in some regions, which can hinder the adoption of eco-friendly travel practices. Motorcycle riders are regarded as the most vulnerable road users in India, where motorized two-wheelers make up 70 % of all vehicles. Between 2009 and 2016, India's total automobile fleet grew by an exponential amount, from 12,77 billion to 23 billion. By 2050, it is anticipated that India would have the most automobiles on the road, with six million new motor vehicles added year.[20] The research was justified by the rising demand for road tourism and the requirement for sustainable development in the sector. As tourism growth places greater pressure on infrastructure and the environment, it is necessary to extend strategies that balance these factors while improving the visitor experience. Traditional methods of route planning and forecasting often fail to account for the dynamic and complex nature of tourist behavior, traffic conditions, and environmental considerations. By addressing this, the research aims to optimize route planning and minimize environmental impacts, such as carbon emissions and traffic congestion. It will assess the integration of multi-source data to improve forecasting accuracy.

The research utilizes the Bi-GRUForest model to capture the dynamic nature of visitor travel preferences, which are influenced by previous behaviors, traffic conditions, and environmental factors.

The resilience and carbon emissions of eighteen resource-based cities (RBCs) in southwest China were examined to use a sophisticated Genetic Algorithm-Deep Belief Network-Kernel Density Estimation (GA-DBN-KD) model for intermediate carbon emission forecasting and create a resilience index system. It investigates city-specific routes to reach the carbon peak around 2023 and 2040 using 16 situations. It provides regulators with information on low-carbon transformation methods for RBCs.(20) To investigate the countries included in the Belt and Road Initiative (BRI) that are affected by tourism in terms of sustainable economic development. Using data from 57 countries, it was discovered that tourism increases adjusted per capita income by 15,2 %, which has a favorable influence on sustainable development. The findings hold up when utilizing different econometric estimate methods.(21) Through in-depth interviews with stakeholders, it investigates how the Nepalese tourist sector contributes to the Sustainable Development Goals (SDGs). The results indicate that although Nepal can achieve the SDGs, a number of problems could prevent them from being fully implemented. The report emphasizes the crucial need for both developed and developing nations to comprehend the relationship between tourism and the SDGs.(22) Destinations greatly benefit from tourism's social impact, which helps local communities grow when responsible stakeholders participate.(23,24,25,26) While the growth of hotels and infrastructure has positive effects, the adoption of tourist lifestyles by locals, along with issues, such as prostitution, theft, illicit trade, and unequal access to social services has negative effects.(27) According to (28), it explores the possibility of integrated rural tourism in rural borderlands impacted by cross-border travel to examine two coastal cross-border areas shows that there are differences in the tourist attractions and lodging options, transit limitations, and asymmetry in the amount of tourism in these areas. The integration of social, economic, and environmental goals to promote the sustainable development of rural highland communities in Chiang Rai, Thailand, was funded by a royal initiative that employs a variety of research techniques, such as in-depth interviews, ethnographic Delphi, and future research.(29) According to (30), it assesses the viability of ice-and-snow tourism in China's 832 impoverished counties. The distribution of tourism associated with glaciers and skiing was found to differ significantly, with ski tourism occurring in low-altitude mountainous regions and glacier tourism mostly occurring in the Qinghai-Tibet Plateau. The potential for medium-to-high-level ISIs is present in 36,0 % of impoverished counties, with 2,5 %, 32,9 %, and 0,2 % of those counties being appropriate for ski activities and glacier excursions, respectively.

METHOD

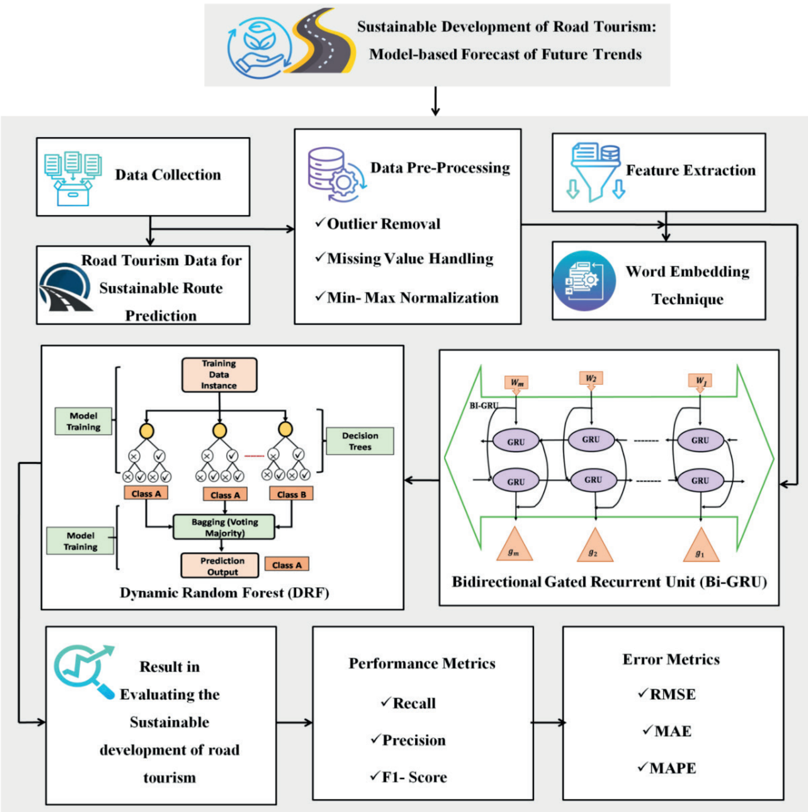

Figure 1. Schematic diagram of methodology flow

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Sustainable development in road tourism aims to address both the environmental and economic impacts of this growing sector. The methodology adopts the Bi-GRUForest model to forecast sustainable road tourism trends, integrating Bi-GRU for route recommendations and DRF for travel pattern analysis, developed by a temporal attention mechanism. Data was gathered from multi-source datasets on environmental factors, road infrastructure, and tourist behavior, preprocessed through outlier removal, missing value handling, and min-max normalization. Real-time data on road conditions and electric vehicle charging stations were incorporated to encourage eco-friendly travel choices. The model was assessed using key metrics like recall, precision, F1-score, MAE, and RMSE, ensuring enhanced sustainability and efficiency.

Data collection

The dataset was collected from open source Kaggle website: https://www.kaggle.com/datasets/ziya07/road-tourism-data-for-sustainable-route-prediction/data. Ten elements were comprised in the dataset: road conditions, traffic congestion level, travel mode, tourist id, travel date, origin country, destination, sustainability score, electric vehicle usage, and carbon emissions. It used to sustain the score; travel is categorized as either sustainable (1) or unsustainable (0) in a binary target column. Building models that maximize road tourism for sustainability can benefit from this dataset.

Data pre-processing

Data pre-processing is an important part of sustainable road tourism because it guarantees the reliability and higher accuracy of models used to predict near-future trends through the resolution of inconsistencies, missing values, and outliers. Thoughtful pre-processing allows for better and clearer choice-making, which is a perfect compromise of tourism growth with environmental sustainability and resource management.

Outlier removal

The removal of outliers guarantees sustainable development of road tourism data representational, describing the usual pattern that prohibits extreme value distortions with predictions that facilitate a better allocation of resources and planning strategically, guiding policymakers in the formulation of more effective, healthier, and sustainable tourism strategies. The removal of outliers simultaneously diminishes the negative environmental impacts while allowing for balanced tourism growth. The analysis, upon being cleared of outliers, becomes realistic, balancing the needs for tourism development.

Handling missing values

Missing values in sustainable road tourism models are crucial for accurate and reliable road tourism data. Incomplete road tourism data can lead to skewed forecasts, hindering decision-making on infrastructure development, resource allocation, and environmental impact assessments. Addressing missing values through imputation or exclusion ensures integrity in sustainability analyses. Accurate inferences about future trends in road tourism can lead to sustainable planning and better decision-making. An efficient imputation mechanism can lead to more insightful findings for green tourism plans.

Min- Max normalization

Min-Mix Normalization is a technique that modifies the original collection of road tourism data linearly. A technique known as "Min-Mix Normalizing" maintains the connections among the initial information to sustain the development process in road tourism. An easy method of road tourism data can correct the position inside a predefined boundary using the help of min-max normalizing, is shown in equation (1).

$$B' = \left(\frac{B - \min valueofB}{\max valueofB - \min valueofB}\right) * (C - D) + D \qquad (1)$$

In B', one among the Min-Max standardized sets of information is contained. B Represents the converted road tourism data if [C,D] is the predefined perimeter and B is the starting region.

Feature extraction using word embedding

Word embedding is important in extracting important features associated with the sustainable development of road tourism through the conversion of textual data, as tourist reviews or social media posts-into numerical forms that can be analyzed. These embedding's provide semantic meaning and allow one to identify some trends, preferences, and concerns out of the huge database of unstructured text. In terms of road tourism, word embedding helps extract insights directly concerned with environmental impact, the quality of infrastructure, and satisfaction levels among travelers. Transforming textual data into actionable features allows for a more accurate forecast and decision-making for sustainable tourism planning. This method can enhance the importance of forecasting and managing future needs of road tourism with a high priority for sustainability.

Bidirectional Gated Recurrent Unit fused Dynamic Random Forest (Bi-GRUForest)

Bi-GRUForest is one of the central algorithms to realize prediction and path analysis regarding the trends of road tourism via its capability of delineating temporal structure and intricate interactions in data.

Dynamic Random Forest (DRF)

A DRF is a type of ensemble learning device that produces hypotheses by fusing the vast majority of predictions from numerous different base models to sustain the development process in road tourism. The DRF is easy to use and effectively specifies road tourism data by reflecting key characteristics. The leaf's pixels are built to produce a subdivision of receptive domain (RD) at each level, and RD serves as the starting point for the matching tree to sustain the development process in road tourism. Each node in the tree is made specifically and it matches a rectangular subset of RD. In each stage of construction, one expanded tree leaf is selected. The estimators in each tree leaf are fitted using evaluation nodes. Each tree encounters a random division of the views regarding the data by assigning each point to the design or estimation component to sustain the development process in road tourism. The distribution of the random vectors W and Z were used to generate the testing instances for the classifiers. $g_1(w)$, $g_2(w)$,..,$g_l(w)$. The monetization feature is shown in equation (2).

$$Nh(W,Z) = bu_l J(g_l(W) = Z) - \frac{max}{i \neq Z} bu_l J(g_l(W) = i) \quad (2)$$

Where J (w) is the measured value, the error's root cause in equation (3).

$$OF^* = O_{W,Z}(mg(W,Z) < 0) \quad (3)$$

The probability of occurring in the wZ dimension is shown by the location of the W,Z space. The margin feature for a DRF is shown in equations (4) and (5).

$$nq(W,Z) = O_\Theta(g(W.\Theta) = Z) - \frac{max}{i \neq Z} O_\Theta(g(W,\Theta)\} \quad (4)$$

Additionally, the value of the classifiers in the set g(W.Θ).

$$T = F_{W,Z} mr(W,Z) \quad (5)$$

In the development of road tourism for sustainable development, the DRF provides robust predictive models for the analysis and forecasting of trends in tourist behavior, infrastructure usage, and environmental effects. With insights into changing patterns of road tourism data, it can deliver the most favorable strategies that help balance the goals of growth and sustainability in the tourism sector. Figure 2 depicts the architecture of DRF.

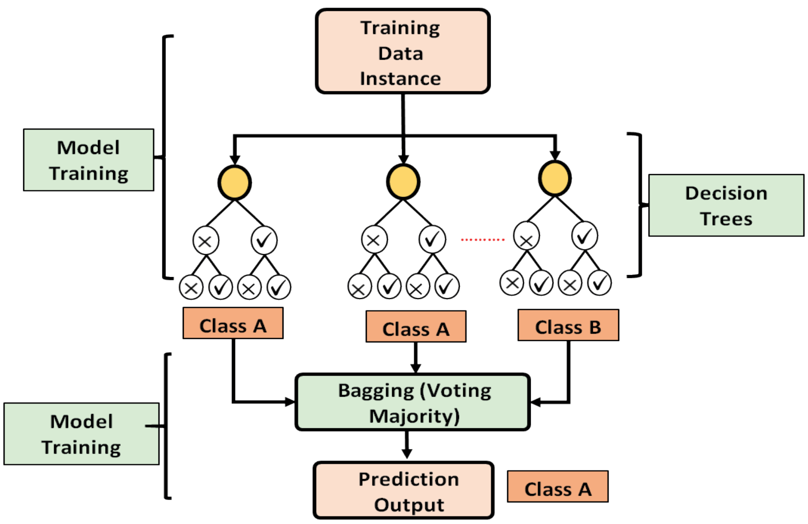

Figure 2. Architecture of DRF

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Bidirectional Gated Recurrent (Bi-GRU)

A bidirectional recurrent neural network (Bi-RNN) is the source of the Bi-GRU unit which consists of two layers of GRUs with different directions of information transmission to sustain the development process in road tourism. A reverse layer is added to the single-layer GRU network in the Bi-GRU configuration to maximize the use of input data. Figure 3 presents the architecture that uses two hidden layers to record information from the past and the future. The present situation acknowledges that ignoring one-way communication can affect the GRU model's prediction performance and is impacted by both past and future data to sustain the development process in road tourism. The current state's output and the same output layer are connected to both hidden layers (zs) is shown in equation (6).

$$zs = [g \gg, g \ll] \quad (6)$$

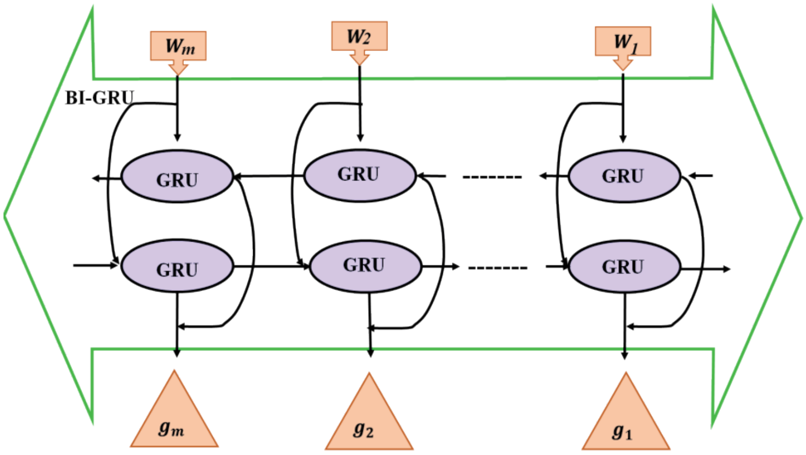

Figure 3. Architecture of Bi-GRU

Similarly, it helps in the allocation of resources through sustainable tourism planning, decision-making, and the further forecasting of long-term environmental impacts with serial consideration of both tourism development and sustainability.

RESULTS

The Python platform and the RAM of a laptop with 8,00 GB are used to access data quickly. Intel® Core i9 Processors and Windows 11 have been utilized. The research proposed a Bidirectional Gated Recurrent Unit fused Dynamic Random Forest (Bi-GRUForest) model for forecasting future trends in sustainable road tourism and considered existing methods, such as Personalized recurrent neural network (P-RecN),[31] Long short-term memory - correlation-based predictor selection (LSTM-CPS).[32]

Performance metrics

To emphasize the need to balance the growth of tourist arrivals with the preservation of the environment during the development of road tourism. Using the Bi-GRUForest modeling approach emphasizes accurate forecasting of future trends, needs for infrastructure, demand, and sustainability practices in providing decision-making support for long-term and sustainable development in the industry. Table 1 and figure 4 present the values of performance metrics.

Table 1. Quantitative values for performance metrics

Methods	Recall (%)	Precision (%)	F1-score (%)
P-RecN[15]	79,4	76,2	78,6
Bi-GRUForest [Proposed]	90,2	89,5	87,9

Recall

Recall that integrating sustainable development in road tourism is about establishing equilibrium between the growth of tourism and the conservation of the environment. The research intends to use Bi-GRUForest based approaches for the projection of future trends and impact on the sector based on infrastructure, demand, and sustainability initiatives. The models help elucidate the prospective challenges and openings through knowledge-aided decision-making for stakeholders in the tourism industry. The proposed method, Bi-GRUForest, has attained higher values in recall (90,2 %) compared to other method of P-RecN (79,4 %).

Precision

Precision sets the sustainable development in road tourism, which is concerned with the balancing of development with environmental and social well-being. The research uses a modeling approach to forecast future trends in demand, infrastructure, and sustainability practices. The research identifies key factors that could influence wise policy decisions aimed at taking the road tourism industry forward for long-term success and minimal adverse impact. The research reinforces the significance of integrating sustainable practices in road tourism development, as a proper means to ensure sustainable economic and environmental benefits for both to communities and travelers. The values of precision in Bi-GRUForest were observed at 89,5 %, which is greater than the P-RecN at 76,2 %.

F1-score

The F1-score forms an important metric in model performance, used for future road tourism predictions. F1-score in the context of sustainable development represent a trade-off between precision and recall and serves as a single number to evaluate how well a model predict outcomes while minimizing false positives and false negatives. This is particularly crucial for sustainable road tourism planning and development; variables like environmental impact and infrastructure requirements must be accurately assessed. The proposed method Bi-GRUForest has attained higher values in recall (88,9 %) than other method, P-RecN (78,6 %).

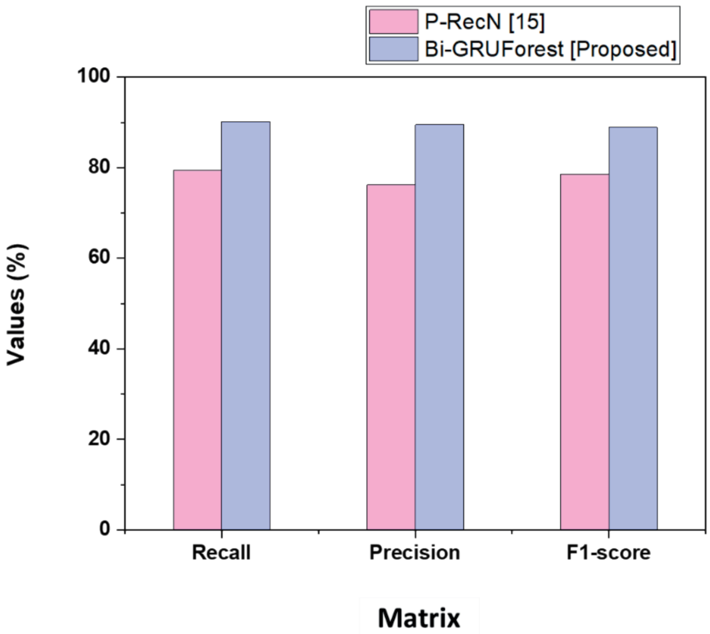

Figure 4. Graphical representation of performance metrics

Error metrics

Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE) are fundamental in predicting tourism dynamics toward road sustainability. With lower MAE values, the model can have a higher degree of accuracy, while lower values of MAPE indicate a comparatively more efficient model. Root Mean Square Error (RMSE) corroborates forecasts based on model estimates to achieve sustainable tourism, infrastructure planning, and environmental impact. Table 2 represents the quantitative values of error metrics in MAE, MAPE, and RMSE.

Table 2. Quantitative values for error metrics

Methods	MAE	MAPE	RMSE
LSTM-CPS[16]	943,06	24,21	1 199,63
Bi-GRUForest [Proposed]	600,01	15,10	700,01

MAE

MAE means the prediction accuracy from installing MAE, which is crucial in projecting tourism dynamics for road sustainability through averaging the contemplated absolute difference between the performed and estimated values. In modeling the expected future trends, the application of MAE guarantees reliable estimates of tourism demand, infrastructure requirements, and environmental impacts. The lowest values of MAE imply the models prefer the ability to support different strategies for sustainable tourism development, as Bi-GRUForest observed 600,0,1 which is lower than the LSTM-CPS of 943,06. Figure 5 presents the MAE.

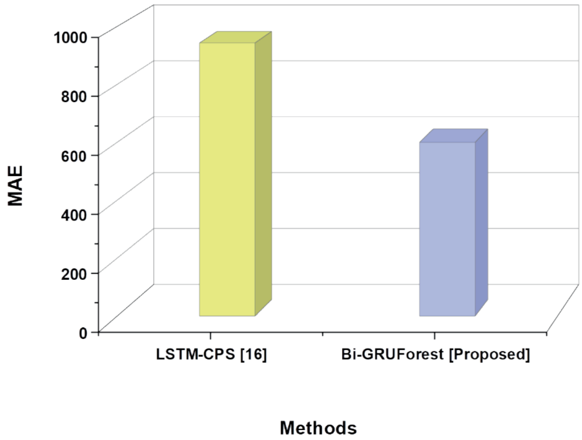

Figure 5. Graphical representation of MAE

MAPE

MAPE is one of the vital performance measures used to evaluate the accuracy of any forecasting model pertaining to road tourism sustainability. This extends sustainable development strategy formulation by servicing infrastructure planning investment, resource allocation, and eco-friendly policies for tourism development initiation in line with future considerations. The value of MAPE is 15.10 in Bi-GRUForest and 24.21 in LSTM-CPS, as shown in figure 6.

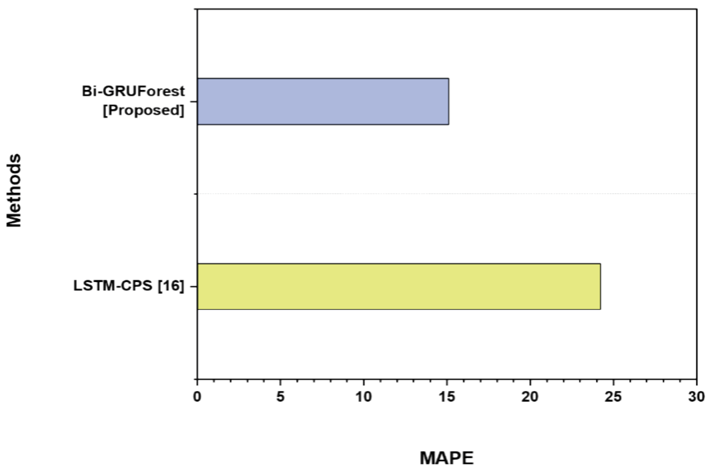

Figure 6. Graphical representation of MAPE

RMSE

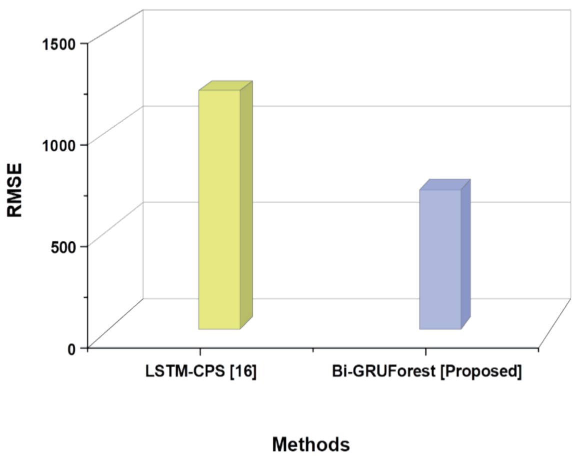

Figure 7. Graphical representation of RMSE

RMSE gauges the efficiency of model-based forecasts in the sustainable road tourism area by measuring the distance between predicted and actual statistics. The lower the RMSE, more accurate tourist demands, infrastructure, and environmental impact forecasts. Therefore, determining the best value of RMSE contributes to an informed decision on balanced economic progression and conservation of nature in the sustainable development of road tourism planning. Figure 7 illustrates the value of RMSE in Bi-GRUForest at 700,01 and LSTM-CPS at 1 199,63.

DISCUSSIONS

Tourism forecasting needs models capable of capturing complex, nonlinear patterns while remaining resilient to abrupt disruptions. Existing approaches, such as P-RecN(16), lack responsiveness to external shocks due to their dependence on historical trends, and their personalized modeling approach incurs high computational costs. LSTM-CPS, although competent in sequential data handling, struggles with high-dimensionality and often overfits, especially when correlation-based feature selection fails to capture nonlinear dependencies. In contrast, the proposed Bi-GRUForest model combines Bi-GRU with decision tree-based reasoning to dynamically capture evolving patterns and nonlinear relationships. From the perspective of the authors, the hybrid architecture provides a more adaptive and scalable forecasting solution, balancing accuracy with computational efficiency. Compared to previous models, it enhances generalization, reduces training overhead, and supports real-time application. Its dependence on historical data, however, has limitations in quickly changing tourism environments. The model's dependence on historical data reduces its ability to quickly adapt to unforeseen disruptions, limiting real-time responsiveness and the incorporation of multi-source real-time data demands substantial computational resources, which might obstruct scalability in resource-constrained regions.

CONCLUSIONS

The research aims to develop a robust, data-driven forecasting model that supports sustainable road tourism through accurate travel demand prediction, environmentally conscious route planning, and efficient infrastructure utilization. Bi-GRUForest advances sustainable road tourism forecasting by aligning route prediction with environmental priorities such as emission control and congestion mitigation. Through the fusion of bidirectional GRU and decision tree reasoning within a temporal attention framework, the model promotes efficient tourist flow and informed route planning. The Bi-GRUForest model is considered a step forecasting method for sustainable road tourism, directing against the shortcomings of traditional approaches. Bi-GRU with DRF in the temporal attention mechanism allows the model to predict travel routes according to sustainability factors, such as carbon emissions and congestion reduction. It achieves strong predictive performance with a recall of 90,2 %, precision of 89,5 %, and F1-score of 87,9 %, alongside reduced error rates 600,01 of MAE, 15,10 of MAPE, and 700,01 of RMSE demonstrating robustness in complex scenarios. Beyond metrics, it enables strategic insights for policymakers and urban planners in designing eco-conscious tourism systems. However, dependence on historical trends limits adaptability to unforeseen shifts. Future research should explore hybrid deep reinforcement learning to enhance real-time, context-aware decision-making in intelligent transportation systems.

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