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ADVANCING URBAN GOVERNANCE IN THE DIGITAL ERA: FROM CLASSICAL STATISTICS TO LSTM DEEP LEARNING FOR PARKING REVENUE PREDICTION

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Abstract. Regional autonomy in Indonesia has increased the responsibility of local governments to enhance public welfare through optimized local revenue. Parking retribution, particularly from on-street parking, serves as an important source of income for Karanganyar Regency, a densely populated and tourism-oriented area with high potential. However, unregulated parking, inconsistent fee collection, and reliance on manual forecasting have resulted in suboptimal revenue outcomes. Existing methods remain limited, depending on simple calculations or linear projections without utilizing modern computational tools. This study compares classical statistical forecasting and Long Short-Term Memory (LSTM) deep learning models to predict parking revenue in Karanganyar Regency. The results show that classical methods capture general trends, while LSTM provides higher accuracy and robustness in handling nonlinear and temporal data. The study highlights the importance of advanced machine learning as a digital governance instrument to improve transparency, optimize revenue management, and support data-driven urban policymaking.

Keywords: digital urban governance, parking revenue prediction, classical statistics, LSTM deep learning

INTRODUCTION

The implementation of regional autonomy in Indonesia has expanded the responsibilities of local governments to enhance public welfare through effective financial management. Within this framework, the optimization of Local Own-Source Revenue plays a strategic role in ensuring fiscal independence and the sustainability of local governance. The enactment of Law No. 28 of 2009 on Regional Taxes and Retributions provides the legal foundation for local governments to collect taxes and fees that directly support public services (Taurisa, 2020). However, despite this regulatory support, the optimization of Local Own-Source Revenue, particularly through retribution mechanisms, remains a persistent challenge for many regions (Mega Christia & Ispriyarso, 2019).

Among the various types of regional levies, on-street parking retribution holds significant potential as a steady source of local income. Classified as a public service retribution, it represents a fee for the use of public space managed by local governments (Amelia, 2024). Karanganyar Regency in Central Java, with its dense population and popularity as a tourist destination, is well-positioned to increase revenue through parking retribution. The heightened mobility of both residents and visitors, especially on weekends and holidays, creates significant demand for parking, presenting a clear opportunity for greater income.

In practice, however, Karanganyar's parking retribution has not yet realized its optimal potential. According to the local Department of Transportation, the main issues include unregulated parking operations, undisciplined fee collectors, and a manual, intuition-based approach to target forecasting. Current forecasting practices rely on simple historical extrapolation and administrative judgment rather than data-driven computation. As a result, revenue targets are often inaccurate and fail to capture seasonal or behavioral patterns in parking activity.

Along with the advancement of technology and data science, forecasting techniques based on machine learning, such as Long Short-Term Memory (LSTM), have been increasingly adopted for

predicting nonlinear and dynamic time series data. For instance, several studies have employed LSTM to forecast parking occupancy in real time, even combining it with weather data and spatial variables to enhance prediction accuracy (Jin et al., 2022; Yang et al., 2019; Zhang et al., 2022). The integration of deep learning into public sector data management aligns with the broader digital transformation agenda observed in both urban and rural governance. Studies such as Utama et al. (2024) demonstrate how digital systems like the Village Data Center (DDC) enhance transparency, efficiency, and inter-agency coordination through e-government applications in financial distribution across local institutions in East Java (Utama et al., 2024). Similarly, comparative research in predictive modeling has shown that deep learning approaches outperform classical statistical methods when handling nonlinear and high-frequency time series data, particularly in dynamic environments such as crowd forecasting and energy prediction (Cecaj et al., 2020; Mynhoff et al., 2018). These advancements underscore the potential of LSTM-based forecasting not only for academic modeling but also as a practical decision-support tool for public revenue optimization. By leveraging temporal data patterns through artificial intelligence, local governments can move toward data-driven governance, improving transparency and accountability in fiscal management while enhancing service delivery to the public.

In this context, the present study aims to compare classical statistical forecasting with LSTM deep learning models in predicting on-street parking revenue in Karanganyar Regency. By integrating modern computational approaches into local financial management, this research seeks to advance the practice of digital urban governance such as enhancing transparency, optimizing revenue administration, and supporting evidence-based policymaking at the regional level. The findings are expected to contribute both practically, by offering data-driven solutions for local governments, and theoretically, by expanding the discourse on artificial intelligence applications in public sector finance.

RESEARCH METHOD

This study uses a quantitative comparative experimental approach to evaluate two forecasting models: Linear Regression, which represents classical statistical methods, and Long Short-Term Memory (LSTM), which represents deep learning techniques, in predicting on-street parking revenue in Karanganyar Regency, Central Java. Linear Regression assumes a linear relationship between predictors and outcome variables, estimating coefficients to minimize error (Sangeetha & Alfia, 2024). LSTM is a variant of Recurrent Neural Networks designed to capture temporal dependencies and long-term patterns through gating mechanisms and memory cells (Koçak, 2024). The main goal is to determine which model provides better predictive accuracy and to show how data-driven forecasting can improve local financial management. The research process involves several key stages, including identifying the problem, collecting relevant data, preparing the dataset, developing the predictive model, training the model, evaluating its performance, and formulating recommendations based on the results. The overall workflow of this research is illustrated in Figure 1.

The study begins with identifying the main issues and reviewing relevant literature to build a strong theoretical foundation. This stage examines previous research on time series forecasting, regression analysis, and neural network models, particularly those using LSTM architecture. The insights from this review help shape the research questions and the overall design of the forecasting framework. The dataset consists of monthly parking ticket records from 2017 to 2021 obtained from the Department of Transportation of Karanganyar Regency. The data represent actual parking revenue performance and are organized in CSV format. The dataset is checked for completeness, consistency, and the absence of missing values to ensure reliability.

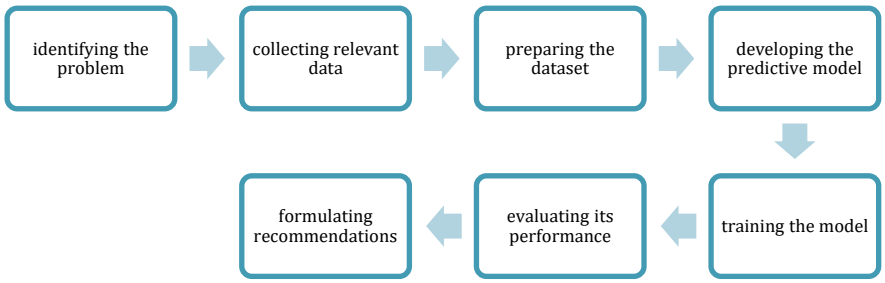

Fig. 1. Research process for predicting parking revenue using linear regression and LSTM deep learning approaches

Data preprocessing involves cleaning inconsistent entries, converting date columns into datetime format, normalizing numerical variables using the Robust Scaler (Nugraha et al., 2024) method for the LSTM model and Linear Regression model. These steps prepare the dataset for analysis and ensure that it is standardized for both model types. Two models are then developed: a Linear Regression model implemented using Scikit-learn and an LSTM-based Recurrent Neural Network built with TensorFlow and Keras. Both models are tested to confirm that they function correctly and can produce initial predictive outputs.

The training process uses data from 2017 to 2020, while the data from 2021 are used for testing. For the LSTM model, an early stopping method is applied to prevent overfitting and to ensure stable convergence between training and validation losses. Model performance is evaluated using two key metrics: Mean Absolute Error (MAE) and Mean Squared Error (MSE) (Tatachar, 2021). These metrics are used to compare predictive accuracy, where lower MAE and MSE values indicate better model performance..

In the final phase, the results are interpreted and policy recommendations are developed. The comparison identifies which model achieves higher precision and reliability in forecasting parking revenue. The findings are analyzed in the context of local financial governance to highlight how artificial intelligence can enhance transparency, efficiency, and evidence-based policymaking. By applying deep learning to revenue forecasting, this research supports the digital transformation of local government and contributes to the development of more data-driven urban governance practices.

RESULT AND ANALYSIS

The results of this study provide empirical evidence on the performance comparison between Linear Regression and Long Short-Term Memory (LSTM) models in forecasting parking retribution revenue in Karanganyar Regency. The analysis is based on monthly data of ticket sales from 2017 to 2021. The dataset was first preprocessed through normalization using the Robust Scaler method to mitigate the impact of outliers, ensuring that extreme values did not distort the learning process. Figure 2 presents the trend of parking ticket sales over five years, with each data point labeled by its corresponding month and year.

As shown in Figure 2, the trend of ticket sales demonstrates a clear seasonal pattern, with significant increases occurring toward the end of each year, particularly in December. These peaks correspond to periods of increased mobility associated with national holidays and local events. Conversely, certain months exhibit notably lower sales, reflecting both seasonal inactivity and possible operational constraints. The labeling of each point in the trend visualization facilitates the identification of temporal cycles and anomalies. The sharp fluctuations indicate the influence of

external factors such as tourism activity, public holidays, and policy enforcement in parking management. The time-series trend suggests the existence of both short-term volatility and long-term periodicity, which are essential characteristics captured effectively by deep learning models like LSTM.

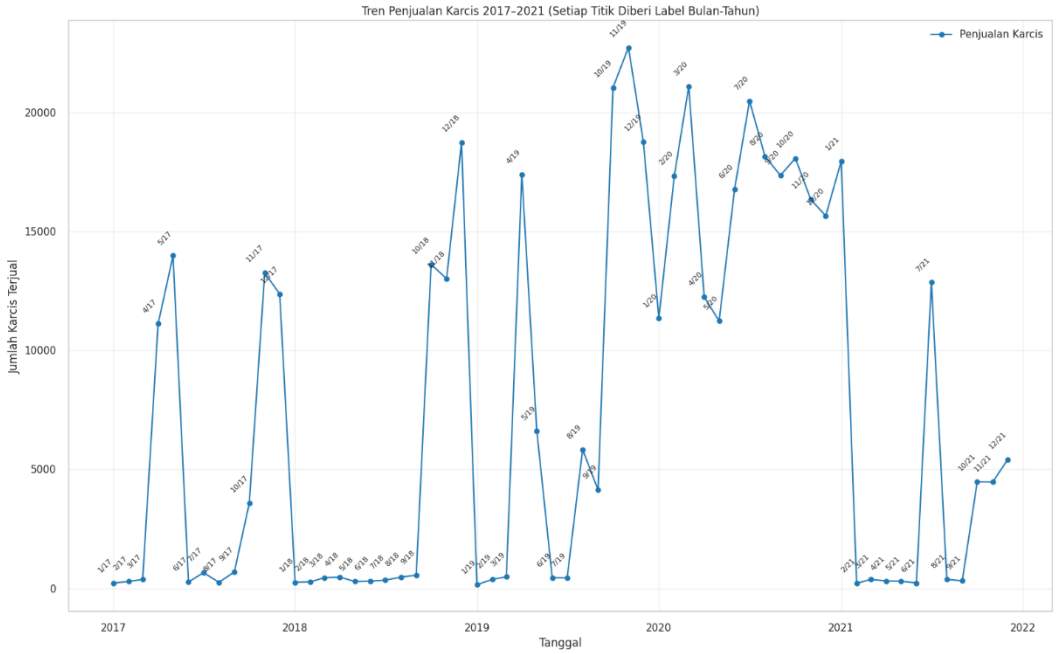

Fig 2. Trend of parking ticket sales (2017–2021).

To further understand the data distribution and identify potential outliers, Figure 3 displays the boxplot of ticket sales per year. The results indicate that 2019 and 2020 had the highest median sales and wider interquartile ranges compared to other years, suggesting greater variability in parking activity during these periods. The presence of outlier points, particularly in 2019 and 2021, reflects extraordinary sales months, possibly linked to special events or changes in traffic management policies. Conversely, the years 2017 and 2018 show narrower distributions and lower median values, consistent with the early stages of policy implementation in parking management. This finding aligns with the theoretical concept of fiscal optimization under decentralization, where the efficiency of local revenue collection evolves gradually through administrative adaptation (Amelia, 2024; Taurisa, 2020).

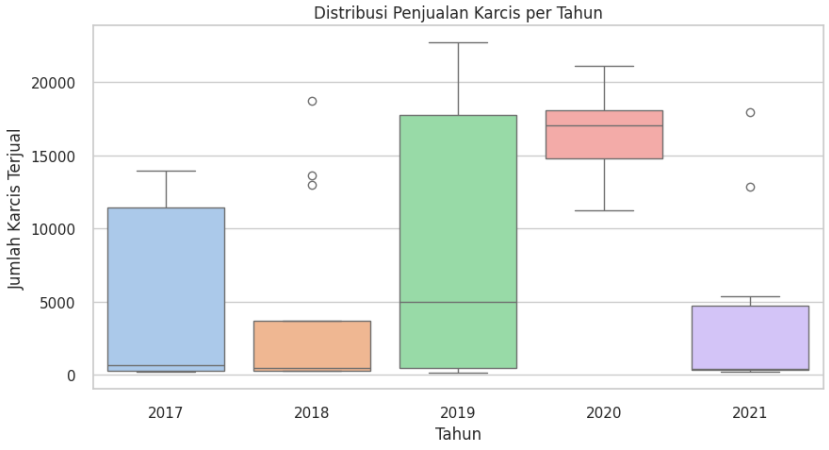

Fig 3. Distribution of parking ticket sales per year.

The comparative visualization in Figure 4 illustrates the predictive performance of the Linear Regression and LSTM models against the actual (scaled) ticket sales data for the year 2021. The results show that the LSTM model (green line) captures the fluctuation pattern of actual data more effectively than the Linear Regression model (orange line), which produces a nearly linear and overgeneralized trend. The actual sales data exhibit nonlinearity and irregular peaks across different months, demonstrating that the underlying revenue behavior cannot be adequately modeled by linear assumptions.

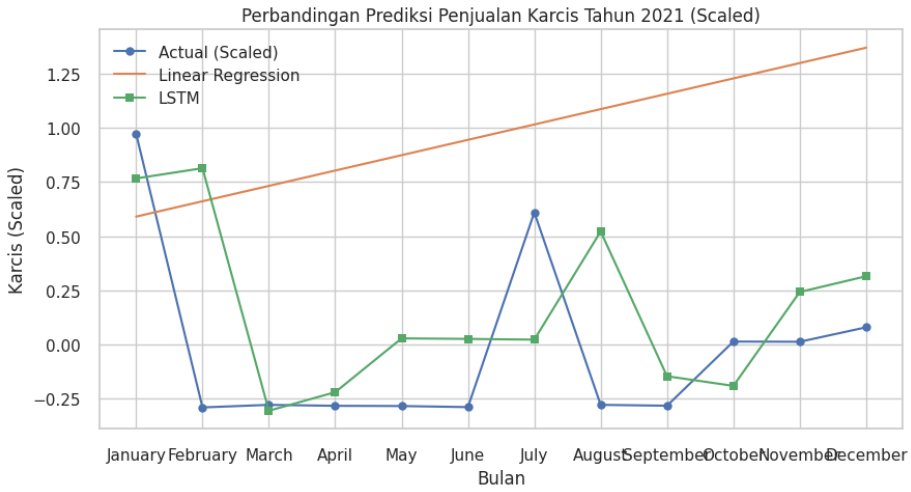

Fig 4. Comparison of actual and predicted ticket sales (2021).

Quantitatively, model performance was evaluated using two standard metrics: Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE). As shown in Table 1, the LSTM model outperformed the Linear Regression model across both evaluation metrics, achieving smaller prediction errors and greater stability in handling nonlinear temporal dynamics.

Table 1. Model performance comparison for 2021 parking ticket sales prediction.

Model	MAE	RMSE
Linear Regression	1.0704	1.1203
LSTM	0.3523	0.4678

The superior performance of LSTM aligns with its theoretical advantage in capturing nonlinear temporal dependencies through gated memory cells (Koçak, 2024). Unlike Linear Regression, which assumes fixed relationships between time and revenue, LSTM dynamically adjusts to sequential variations, learning both short-term fluctuations and residual long-term trends. In this study, the model's learning capability is particularly beneficial in handling irregular patterns observed in 2021 as an atypical year affected by mobility restrictions and post-pandemic economic adjustments.

These findings reinforce previous studies suggesting that deep learning models outperform classical approaches in volatile and seasonal forecasting environments (Cecaj et al., 2020; Jin et al., 2022). In the context of regional financial management, applying LSTM-based forecasting enables more realistic revenue planning and adaptive target setting. The model's predictive behavior demonstrates how artificial intelligence can function as a decision-support tool, providing local governments with data-driven insights for more precise financial control and performance evaluation. Moreover, empirical research shows that AI-based forecasting in local government financial systems can significantly enhance predictive accuracy and optimize fiscal decision-making, indicating that similar implementation could boost revenue for Karanganyar Regency through improved identification of growth opportunities and adaptive financial strategies (Yonan, 2023).

CONCLUSION

This study provides empirical evidence that the Long Short-Term Memory (LSTM) model outperforms traditional Linear Regression in forecasting on-street parking retribution revenue in Karanganyar Regency. The superior performance of LSTM is attributed to its capability to model nonlinear, time-dependent fluctuations in revenue data, which are strongly influenced by seasonal and external factors such as tourism activity and public holidays. Quantitatively, the LSTM model achieved higher predictive accuracy with MAE = 0.3523 and RMSE = 0.4678, compared to the Linear Regression model which recorded MAE = 1.0704 and RMSE = 1.1203.

From a policy perspective, integrating LSTM-based forecasting into local government financial systems can improve target accuracy, optimize fiscal planning, and strengthen accountability in revenue administration. The implementation of artificial intelligence within public finance aligns with Indonesia's broader e-government transformation agenda, advancing the shift toward data-driven governance. Future studies are recommended to expand the dataset, incorporate additional variables such as weather, mobility, and event data, and test hybrid models to further enhance predictive precision and applicability in other sectors of local revenue management.

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