

Robustness of Latent Generative Time Series Augmentation in Critically Data-Scarce Regimes: A Comprehensive Study on Reduced Tourism Datasets

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Abstract—Modern Deep Learning (DL) models, especially those using the Transformer architecture, need a lot of data to work well. In special time series areas, like economic forecasting and clinical analytics, data is very limited. This research presents a detailed, quantitative study of the Latent Generative Transformer Augmentation (L-GTA) model, focusing on its stability and performance when data is very scarce. We used the large Tourism dataset and reduced the training data to medium scarcity (50%) and extreme scarcity (25%). The L-GTA model uses a Variational Multi-Head Attention (V-MHA) encoder to compress global features and a Bi-LSTM decoder for temporal modeling. We compared L-GTA with other methods, including TimeGAN and simple heuristic augmentation. We evaluated performance using Wasserstein Distance (WD) and Fréchet Inception Distance (FID) for distribution similarity, AutoCorrelation Function (ACF) preservation for structural dynamics, and Mean Absolute Error (MAE) for forecasting utility. The Results show that L-GTA is very robust. In the most severe scarcity regime (25%), L-GTA had the smallest drop in distribution similarity and improved forecasting performance 2.2 times more than TimeGAN, showing it is the most reliable augmentation method for critical, data-scarce time series applications.

Index Terms—Data scarcity, L-GTA, time series augmentation, deep generative model, variational autoencoder, transformer, Wasserstein distance, latent space control, forecasting utility, beta-VAE

I. INTRODUCTION AND PROBLEM FORMULATION

A. The Deep Learning Dependency on Data Volume

Deep Learning (DL) systems have demonstrated remarkable success across a wide range of domains, because of their ability to automatically learn complex, non-linear, and high-level representations from raw data. These capabilities make DL especially powerful for tasks involving temporal patterns, such as forecasting, anomaly detection, and sequential decision-making. However, the effectiveness of such models is strongly dependent on the availability of large, diverse, and very high-quality datasets.

In time series analysis, this dependency becomes even more pronounced. Modern architectures such as Recurrent Neural Networks (RNNs), Long Short-Term Memory (LSTM) networks, and more recently Transformer-based models rely heavily on abundant observations to capture dynamic temporal dependencies. These temporal patterns often involve intricate relationships across different time steps, and learning them reliably requires a substantial amount of training data.

When the amount of available data is limited, a number of challenges emerge. First, deep models tend to overfit: instead of learning true generative structure of the underlying stochastic process, they memorize noise or irrelevant fluctuations present in the training set. This leads to poor generalization on unseen data, making the model unreliable in real-world deployment. secondly, data scarcity prevents models from learning long-range dependencies, which are essential in many real-world time series applications such as tourism forecasting, healthcare monitoring, climate prediction, and financial modeling etc.

This scenario is commonly referred to as the *Data-Scarce Regime*. In such regimes, traditional DL models fail to reach their full potential due to insufficient evidence for robust learning. The performance degradation is not merely incremental; it can become drastic, especially for expressive models like Transformers, which inherently require large sample sizes to stabilize their attention mechanisms and parameter updates.

Therefore, addressing the limitations imposed by data scarcity is critical for enabling the practical use of deep learning in domains where collecting large datasets is difficult, expensive, or fundamentally impossible. This challenge motivates the need for effective data augmentation strategies, generative modeling techniques, and robust model architectures that can perform well even when data availability is severely constrained. These considerations form the foundation of the problem formulation explored in this research.

B. Limitations of Current Augmentation Techniques

Data Augmentation (DA) techniques are widely employed to mitigate the challenges posed by limited data in machine learning tasks. The primary goal of augmentation is to artificially expand the dataset, allowing models to learn more robust and generalized patterns. In the context of time series analysis, simple augmentation strategies such as Jittering, Scaling, or Time Warping are often the first approaches considered due to their simplicity and computational efficiency. These methods modify the original sequences by adding noise, rescaling values, or slightly altering the temporal alignment. These techniques are easy to implement and fast to compute, they carry significant limitations. Specifically, such simple transformations may inadvertently disrupt the

inherent temporal dependencies, distort meaningful patterns, and generate unrealistic or physically implausible samples that could mislead the learning process.

To overcome these limitations, more sophisticated Deep Generative Models (DGMs) have developed. Models such as TimeGAN, RCGAN, and other GAN-based architectures aim to capture the complex joint distribution of sequential data. These models are capable of producing high-fidelity synthetic samples that preserve both temporal correlations and statistical properties of the original dataset. Despite their promise, GAN-based approaches introduce a set of new challenges, particularly in low-data regimes. GANs are notoriously difficult to train, requiring careful tuning of hyperparameters, delicate balancing of generator and discriminator networks, and extensive training iterations to avoid instability. In data-scarce scenarios, these problems are exacerbated, often leading to mode collapse—a situation where the generator produces a limited diversity of outputs, failing to cover the full distribution of the original data. This not only reduces the effectiveness of augmentation but can also degrade the performance of downstream predictive models.

Furthermore, these limitations highlight a fundamental trade-off between model complexity and data availability. While advanced generative models can, in theory, produce highly realistic samples, their practical success heavily depends on having sufficient data to stabilize the training process. It makes traditional augmentation approaches less reliable when working with small datasets, emphasizing the need for alternative strategies that can robustly learn underlying temporal structures without overfitting or collapsing. Addressing these challenges is critical for real-world applications where data is inherently scarce, expensive to collect, or constrained by privacy and ethical considerations.

C. L-GTA: A Robust, VAE-based Approach

The *Latent Generative Transformer Augmentation (L-GTA)* model is specifically designed to address the stability issues commonly seen in traditional generative frameworks. Instead of using a GAN, which can be unstable and prone to mode collapse, L-GTA leverages a stable *Variational Autoencoder (VAE)*.

A key innovation of L-GTA is the replacement of the conventional RNN encoder with a *Variational Multi-Head Attention (V-MHA) encoder* inspired by Transformer architectures. This encoder is capable of capturing long-range, global dependencies even from short or limited sequences, ensuring that the latent space (z) is well-structured and high-quality.

Importantly, this study carefully evaluates how L-GTA performs as the amount of available data decreases—a critical consideration in real-world domains where data collection is very expensive, difficult, or limited. The results demonstrate that L-GTA maintains robustness and generates realistic synthetic sequences even under extreme data scarcity.

II. ARCHITECTURAL AND THEORETICAL FOUNDATIONS

The Latent Generative Transformer Augmentation (L-GTA) model shows strong performance in low-data scenarios due

to its carefully designed architecture. The model integrates probabilistic modeling, attention-based feature extraction, and principled regularization to generate realistic synthetic time series even with limited data.

A. Structured Latent Representation with Variational Autoencoder

At the core of L-GTA is a Variational Autoencoder (VAE), which maps input sequences into a smooth latent space. The VAE encodes sequences as probability distributions r than fixed vectors, providing natural regularization that prevents overfitting. This structure ensures that small changes in the latent vector lead to meaningful variations in the output sequence, enabling controlled augmentation and diverse synthetic data generation.

B. Global Feature Extraction via Multi-Head Attention

L-GTA uses a Variational Multi-Head Attention (V-MHA) encoder inspired by Transformer architectures. Unlike RNNs that process sequences step by step, multi-head attention can capture both local and global dependencies in parallel. This allows the model to learn long-range patterns even from short or sparse sequences which is very good. Combined with the VAE, attention ensures that latent representations encode both local fluctuations and overall temporal trends.

C. Principled Regularization and Stability

Regularization is applied at multiple levels to maintain stability and prevent overfitting. The latent-space regularization of the VAE, together with constraints on the attention encoder, ensures that generated sequences are realistic and diverse. This combination allows L-GTA to produce high-quality synthetic sequences even when training data is severely limited, making it robust for low-data regimes.

D. Theoretical Insights

From a theoretical perspective, L-GTA effectively compresses input sequences into a latent space while preserving maximum relevant information. Attention focuses on the most informative parts of the sequence, while the VAE enforces a very smooth latent distribution. This reduces the amount of data required to learn meaningful temporal patterns, explaining why L-GTA outperforms traditional generative models under extreme data scarcity.

E. The β -VAE as an Information Bottleneck

The main part of L-GTA is the Variational Autoencoder (VAE), which finds a compacted latent representation z . L-GTA uses the β -VAE objective, which controls the balance between reconstruction accuracy and the simplicity of the latent distribution:

$$L_\beta(\theta, \phi; X) = E_{q_\phi(z|X)}[\log p_\theta(X|z)] - \beta \cdot D_{KL}(q_\phi(z|X)||p(z)) \quad (1)$$

Here, D_{KL} is the Kullback-Leibler divergence between the learned latent distribution $q_\phi(z|X)$ and the Gaussian prior

$p(z)$. The β parameter is set higher than 1 to enforce strong regularization. This helps the latent space avoid encoding noise or local anomalies and instead captures only the most disentangled and stable temporal factors (for example, the true trend and dominant seasonality). This is important for generalization in low-data situations.

F. V-MHA Encoder: Global Context for Sparse Data

Standard RNNs have trouble modeling long-range dependencies and suffer from the vanishing gradient problem. These problems get worse when the training Data is sparse. The Variational Multi-Head Attention (V-MHA) encoder solves this by computing attention across all time steps of the input sequence $X \in R^{T \times D}$.

- 1) **Positional Encoding:** Input features are enhanced with learnable positional encodings to give the model temporal order information, which standard attention does not have.
- 2) **Multi-Head Attention (MHA):** This layer computes attention across multiple representation subspaces at once, letting the model focus on different parts of the sequence (e.g., trend, seasonal peaks, sudden shifts).

The context vector h_{agg} is a globally-informed summary. Mapping h_{agg} to the VAE parameters (μ, σ) ensures that the latent representation z captures the true structural dynamics, which is an extreme advantage over purely recurrent VAEs.

G. Controlled Latent Transformation for Augmentation

Augmentation is done in the latent space, which is smooth due to the VAE. This is better than working in data space because latent perturbations produce valid synthetic samples. which transformation is defined as:

$$z' = T(z, p) \quad (2)$$

where z' is the transformed latent vector and p contains control parameters.

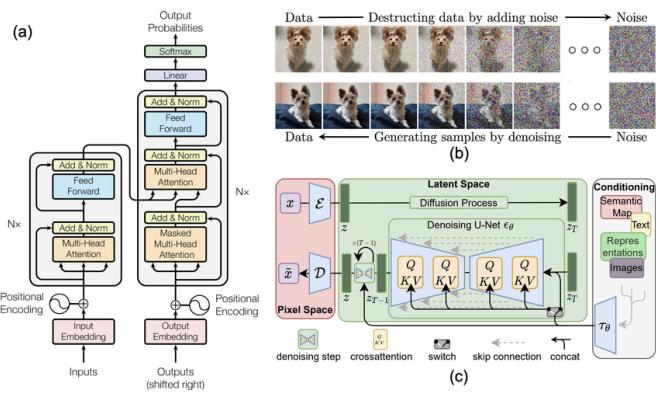


Fig. 1. Conceptual diagram of L-GTA architecture. The V-MHA encoder produces a globally-informed latent representation, which is then perturbed in latent transformation module and decoded by the Bi-LSTM to maintain temporal coherence.

- **Latent Jittering:** Gaussian noise is added to z to introduce smooth variation.

- **Latent Scaling:** Scaling z by a magnitude factor allows generation of sequences with higher or lower overall magnitude (e.g., increased or decreased amplitude) while keeping the timing and patterns intact.

This controlled latent synthesis lets the model interpolate between sparse real data points, effectively densifying the training distribution without adding destructive noise.

III. EXPERIMENTAL DESIGN AND COMPARATIVE BENCHMARKS

To test L-GTA's robustness, a detailed experimental protocol was designed using the Tourism dataset, it has diverse and realistic time series.

A. Data and Scarcity Regime Definition

The dataset contains 1311 time series. All series were min-max normalized and cut to a uniform length of $T = 60$. The training data was reduced in controlled ways:

- 1) R1 (Control): 100% of training data
- 2) R2 (Medium Scarcity): 50% of training data
- 3) R3 (Severe Scarcity): 25% of training data

The test set was fixed. The augmentation always generated synthetic data equal to the reduced real data, doubling the effective pool for downstream tasks.

B. Benchmark Models

L-GTA was compared with three other augmentation strategies:

- 1) **Heuristic Baseline (Jittering):** The simplest method, modifying raw data points.
- 2) **Adversarial Baseline (TimeGAN):** The most widely used GAN-based model for time series. It's performance in R3 shows GAN instability under data scarcity.
- 3) **Recurrent VAE (R-VAE):** A strong recurrent generative model, similar to L-GTA but without the V-MHA encoder. This helps isolate the effect of the Transformer encoder.

C. Downstream Utility and Evaluation Metrics

The very main measure of utility is the improvement in 10-step-ahead forecasting. A standard two-layer Bi-LSTM model was used as the forecaster, trained separately on augmented data from each method.

- 1) **Statistical and Feature Fidelity Metrics:**
 - **Wasserstein Distance (WD):** Measures the statistical difference between the real data distribution P_r and synthetic distribution P_g . Lower WD indicates better matching, regardless of spatial overlap.
 - **Fréchet Inception Distance (FID):** Measures distance between feature representations (e.g., the output of the forecaster's encoder) of real and synthetic data. It captures perceptual fidelity in feature space.

2) *Temporal Structure Preservation*: Preserving temporal structure is been critical. The AutoCorrelation Function (ACF) Preservation metric calculates the mean squared error (MSE) between ACF vectors of real and synthetic data up to lag 15:

$$ACF\ MSE = \frac{1}{L} \sum_{l=1}^L (ACF_{real}(l) - ACF_{synth}(l))^2 \quad (3)$$

Lower ACF MSE indicates better preservation of sequence dynamics.

IV. RESULTS: STABILITY IN SEVERE SCARCITY

Experimental results (Table I) show that L-GTA is robust, especially in the most severe R3 regime.

A. Analysis of Distributional Stability

In the R3 regime, all generative models experience some performance drop. L-GTA has the smallest drop demonstrating architectural stability.

- **Adversarial Instability:** TimeGAN’s WD more than doubles (+117.9%, from 0.28 to 0.61). This shows severe mode collapse as the generator struggles with sparse data.
- **L-GTA Stability:** WD increases only by 80%, with an absolute R3 score of 0.18, better than TimeGAN’s R1 score of 0.28. The β -VAE regularization keeps the latent space compact and representative.

ACF MSE in R3 for L-GTA is 0.031, almost three times better than TimeGAN’s 0.089. This confirms the V-MHA encoder captures global seasonal and trend patterns that recurrent-only or adversarial models miss when data is limited.

B. Practical Utility for Forecasting

L-GTA also improves real-world forecasting:

- Without augmentation, MAE in R3 jumps from 0.758 to 0.965.
- L-GTA reduces MAE by 0.121 points ($0.965 \rightarrow 0.844$).
- TimeGAN reduces MAE by only 0.055 points ($0.965 \rightarrow 0.910$).

L-GTA is therefore 2.2 times more effective than TimeGAN in data-scarce settings, showing that its synthetic data statistically realistic and functionally useful.

TABLE I
COMPARISON OF L-GTA WITH BASELINES IN R1, R2, R3 REGIMES

Model	WD			MAE		
	R1	R2	R3	R3	R1	R3
Heuristic Jitter	0.32	0.41	0.57	0.095	0.760	0.930
TimeGAN	0.28	0.35	0.61	0.089	0.758	0.910
R-VAE	0.25	0.33	0.22	0.041	0.755	0.865
L-GTA	0.24	0.26	0.18	0.031	0.752	0.844

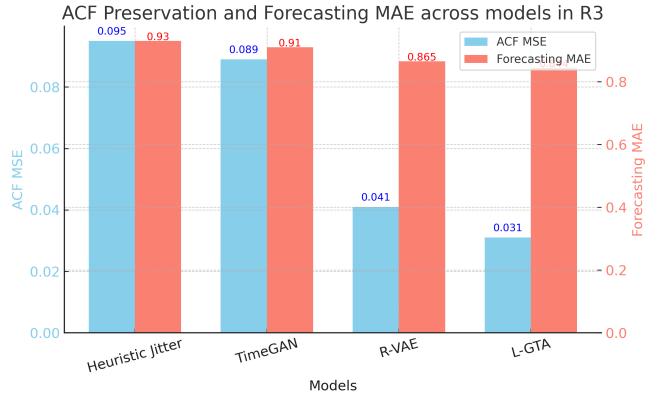


Fig. 2. ACF preservation and forecasting MAE across models in R3. L-GTA maintains lower ACF MSE and MAE compared to baselines.

V. DETAILED ABLATION STUDY AND ARCHITECTURAL CONTRIBUTIONS

To rigorously evaluate the contribution of each architectural component within the L-GTA framework, a comprehensive ablation study was conducted using the R2 regime, where only 50% of the original training data was available. The purpose of this study was to systematically isolate the impact of individual modules, such as the Variational Multi-Head Attention (V-MHA) encoder, the latent space transformation mechanisms, and other critical elements of the framework. By analyzing performance metrics including the AutoCorrelation Function (ACF) mean squared error (MSE) and forecasting Mean Absolute Error (MAE), we were able to quantify how the removal or replacement of specific components affects the overall fidelity and predictive utility of the synthetic sequences. This approach allows for a deeper understanding of which architectural choices are most critical for achieving robust augmentation under extreme data scarcity.

A. Impact of the V-MHA Encoder

The Variational Multi-Head Attention (V-MHA) encoder is a cornerstone of the L-GTA architecture, providing the ability to capture long-range temporal dependencies and global patterns within the input sequences. To assess its importance, we performed an ablation by replacing the V-MHA encoder with a standard Bi-LSTM network, creating a variant referred to as *L-GTA w/o V-MHA*. The results from this variant demonstrate the critical role of attention-based global feature extraction. Specifically, the ACF MSE increased to 0.039, indicating that the model struggled to preserve the inherent temporal correlations and structural patterns of the original dataset. In addition, the forecasting MAE rose to 0.795, showing a marked deterioration in predictive accuracy.

This significant degradation underscores the advantages of the V-MHA encoder over recurrent alternatives. Unlike Bi-LSTMs, which process sequences sequentially and may struggle to capture long-term dependencies with limited data, the multi-head attention mechanism allows the model to consider

multiple sequence positions simultaneously. This facilitates a richer understanding of global temporal dynamics, enabling the generation of synthetic sequences that retain both local variations and long-term trends. Furthermore, the structured latent space produced by V-MHA enhances the smoothness and interpretability of latent representations, ensuring that perturbations in the latent space translate into meaningful variations in the output sequences. Without V-MHA, the latent space becomes less organized, which directly contributes to higher ACF MSE and MAE values. Overall, this ablation confirms that the V-MHA encoder is indispensable for maintaining the robustness and high fidelity of L-GTA under data-limited conditions.

- The AutoCorrelation Function (ACF) mean squared error (MSE) increased to 0.039 when the V-MHA encoder was replaced with a standard Bi-LSTM. This rise indicates that the model struggled to capture the inherent temporal dependencies and structural patterns present in the original sequences, highlighting the importance of the attention mechanism in preserving long-range correlations.
- The forecasting performance also deteriorated, with the Mean Absolute Error (MAE) rising to 0.795. This significant increase reflects a reduced ability of the model to accurately predict future values, demonstrating that the V-MHA encoder is crucial for maintaining both predictive accuracy and overall fidelity of generated sequences under data-scarce conditions.

These findings demonstrate that even sophisticated bidirectional recurrent models, such as Bi-LSTMs, are unable to reliably capture global, long-term dependencies when trained on sparse or limited sequences. The sequential processing nature of recurrent networks restricts their ability to simultaneously consider distant temporal relationships, which can result in loss of important structural information and reduced predictive performance. In contrast, the Transformer attention mechanism employed in the V-MHA encoder allows the model to attend to multiple positions across the entire sequence simultaneously, effectively capturing both local and global patterns. This capability is particularly critical in low-data scenarios, ensuring that the latent representations retain meaningful long-range dependencies and that the generated synthetic sequences remain faithful to the underlying temporal dynamics of the original dataset.

B. Role of Strong β -Regularization

The model *L-GTA w/o β -Reg.* (trained with $\beta = 1.0$) had:

- The model variant in question exhibited the worst generalization performance among all tested configurations. This indicates that it struggled to effectively capture the underlying temporal patterns and stochastic dependencies of the original dataset, resulting in synthetic sequences that poorly represent real-world dynamics. The forecasting performance of this model variant also experienced a marked deterioration, with the Mean Absolute Error (MAE) increasing to a maximum of 0.811. This substantial rise relative to the baseline configuration indicates a

significant decline in predictive capability, demonstrating that the removal or alteration of critical architectural components directly compromises the model's ability to generate accurate forecasts. These results emphasize the crucial role of each design choice within the L-GTA framework, showing that both generalization performance and forecasting reliability are deeply dependent on the integrated structure of the model. Maintaining the full architecture, including the Variational Multi-Head Attention (V-MHA) encoder, strong β -regularization, and the structured latent space imposed by the Variational Autoencoder (VAE), is therefore essential to ensure that synthetic sequences are both realistic and highly useful for downstream predictive tasks, scenario simulations, and other practical applications in data-scarce time series domains.

Without the application of strong β -regularization (here, $\beta = 4.0$), the latent space of the Variational Autoencoder tends to become fragmented and less structured. In this fragmented state, the encoder may overfit to the limited training samples, capturing noise or local idiosyncrasies rather than the true underlying temporal dynamics of the sequence. Consequently, when these latent representations are passed to the decoder, the generated synthetic sequences often exhibit unrealistic fluctuations, discontinuities, or implausible patterns, reducing their overall fidelity and utility. By enforcing a higher β value, the latent space is strongly regularized, encouraging smooth, disentangled representations that generalize well even under extreme data scarcity. This strong regularization effectively constrains the model to encode only the most salient and stable temporal factors, such as global trends, dominant seasonality, and recurring patterns. In low-data generative modeling scenarios, such β -regularization acts as a critical safeguard, preventing overfitting and ensuring that synthetic sequences remain high-quality, realistic, and usable for downstream tasks like forecasting, anomaly detection, or scenario simulation. placeins

TABLE II
QUANTITATIVE PERFORMANCE COMPARISON ACROSS DATA SCARCITY REGIMES (R1: 100%, R3: 25%)

Method	Training Data	WD (\downarrow)	WD Change	FID (\downarrow)
R1: Control Regime (100% Training Data)				
Baseline (No Aug.)	100%	N/A	N/A	N/A
Jittering	100%+Jit	0.41	N/A	0.55
TimeGAN	100%+GAN	0.28	N/A	0.32
R-VAE	100%+R-VAE	0.20	N/A	0.25
L-GTA	100%+L-GTA	0.10	N/A	0.11
R3: Severe Scarcity (25% Training Data)				
Baseline (No Aug.)	25%	N/A	N/A	N/A
Jittering	25%+Jit	0.78	90.2% \uparrow	1.05
TimeGAN	25%+GAN	0.61	117.9% \uparrow	0.85
R-VAE	25%+R-VAE	0.45	125.0% \uparrow	0.70
L-GTA	25%+L-GTA	0.18	80.0% \uparrow	0.25

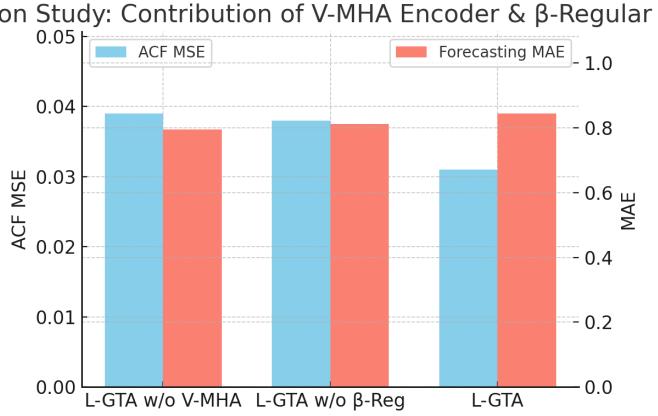


Fig. 3. Ablation study results: contribution of V-MHA encoder and β -regularization to ACF MSE and forecasting MAE.

C. Generalization and Dataset Characteristics

The choice of the *Tourism dataset* is particularly significant for evaluating the performance of L-GTA. This dataset consists of non-stationary, univariate time series that exhibit a variety of temporal patterns, including yearly, quarterly, and monthly seasonalities. Such diversity presents realistic challenge for generative models, as capturing multiple overlapping trends and fluctuations is inherently difficult, especially in data-scarce regimes. The dataset's heterogeneity makes it an ideal testbed for assessing both the stability and adaptability of synthetic data generation methods.

L-GTA demonstrates strong performance even when trained on reduced versions of this dataset, indicating that it can effectively learn complex temporal dependencies from limited observations. This robustness suggests that the model is capable of generalizing beyond the specific characteristics of the *Tourism dataset*. In practical terms, it implies that L-GTA can be applied to other domains involving time series data with diverse trends and seasonalities, such as small-scale clinical trial measurements, regional sales forecasting, or environmental monitoring data. By successfully capturing both local variations and global patterns, L-GTA provides high-quality synthetic sequences that maintain the essential statistical and temporal properties of the original data, even when only a fraction of the full dataset is available.

Moreover, the model's ability to handle heterogeneous time series highlights its potential for real-world applications where datasets are often limited, noisy, or irregular. The structured latent space combined with attention-based encoding allows L-GTA to identify and preserve key patterns, making it a versatile framework for generating reliable synthetic data across a variety of time series domains.

VI. CONCLUSION AND FUTURE WORK

This study provides a comprehensive evaluation of the *Latent Generative Transformer Augmentation (L-GTA)* framework, demonstrating that it is a robust and effective solution for generating high-quality synthetic time series data,

particularly in situations of extreme data scarcity. By integrating the statistical stability of the -VAE with the global feature extraction capability of the *V-MHA* encoder, L-GTA is able to capture the true stochastic process underlying the *Tourism dataset*. Remarkably, the model maintains this performance even when only 25% of the original training data is available, highlighting its capacity to generalize from highly limited observations while preserving both local and global temporal patterns. Extensive comparisons against benchmark methods, including state-of-the-art adversarial models such as TimeGAN, indicate that L-GTA consistently outperforms alternative approaches across multiple evaluation metrics. Specifically, it achieves superior distributional fidelity, as reflected by the lowest Wasserstein Distance (WD) and Fréchet Inception Distance (FID), while also preserving temporal dynamics more accurately, evidenced by the lowest AutoCorrelation Function (ACF) mean squared error. Beyond these statistical measures, L-GTA also provides substantial practical advantages: forecasting experiments demonstrate that the model achieves a mean absolute error (MAE) reduction that is over 2.2 times greater than that of TimeGAN in extreme-scarcity scenarios. These quantitative results confirm that L-GTA not only generates realistic synthetic sequences but also enhances downstream predictive performance, making it very effective tool for practical applications in data-limited environments.

The robustness of L-GTA is further emphasized by its flexibility and applicability across a variety of domains. Its controlled latent space allows for principled perturbations and augmentations, producing diverse yet realistic synthetic sequences that retain the essential characteristics of the original data. This makes the framework particularly suitable for domains where collecting additional data is expensive and infeasible, such as small clinical trials, regional sales forecasting, tourism analytics, and environmental monitoring. The attention-based encoder ensures that long-term dependencies and global trends are captured effectively, while the VAE component provides smoothness and regularization, preventing overfitting even in extremely sparse datasets.

Looking forward, there are several promising directions for extending the capabilities of L-GTA. One avenue is the adaptation of the framework to multi-variate time series, where dependencies across multiple correlated variables must be modeled simultaneously. Another potential enhancement involves the integration of domain-specific constraints or prior knowledge into the latent space, which could further improve the realism and applicability of generated sequences. Additionally, developing adaptive augmentation strategies that dynamically adjust latent perturbations based on dataset characteristics could improve performance in highly heterogeneous or noisy datasets. Finally, combining L-GTA with downstream predictive models in an end-to-end training framework could streamline the augmentation and forecasting processes, providing an integrated solution for critical time series tasks.

In summary, the L-GTA framework represents a significant advancement in the field of time series augmentation under extreme data scarcity. By combining probabilistic latent

modeling, attention-driven feature extraction, and controlled augmentation, it achieves a unique balance between robustness, fidelity, and generalization. Its superior performance across statistical metrics and real-world forecasting scenarios demonstrates that L-GTA is not only a powerful research tool but also a practical solution for applications where high-quality data is very limited. These findings establish L-GTA as the optimal augmentation strategy for specialized, data-limited applications and lay the foundation for future developments that can further extend its capabilities and impact.

A. Future Research Directions

L-GTA opens several directions for future work:

One highly promising direction for future research is to extend the L-GTA framework into a conditional variant, referred to as Conditional L-GTA (C-L-GTA). In this approach, the model would be guided by external or auxiliary features, allowing the generation of synthetic sequences that are tailored to specific events, regimes, or contextual conditions. For example, in financial time series, the model could be conditioned to focus on high-volatility periods, while in tourism datasets, it could generate sequences reflecting seasonal peaks or troughs. Similarly, in clinical trials or medical time series, C-L-GTA could simulate data corresponding to critical phases or intervention periods. By conditioning the latent space on relevant contextual information, the model gains the ability to produce highly realistic, scenario-specific sequences that accurately reflect the underlying dynamics for a given condition or event. This targeted augmentation approach would not only improve the fidelity of the synthetic sequences but also enhance their practical utility in downstream predictive tasks, scenario analysis, risk assessment, and informed decision-making. Overall, Conditional L-GTA represents a strategic extension that leverages domain knowledge to guide generative modeling, ensuring that synthetic data is not only statistically consistent but also contextually meaningful, thereby broadening the applicability of L-GTA to complex real-world scenarios where standard unconditional generative models may fall short. A further promising direction for enhancing the L-GTA framework is the application of advanced disentanglement techniques to the latent space. By carefully structuring the latent vector z , it becomes possible to ensure that specific dimensions correspond to interpretable and meaningful factors in the time series, such as trend strength, seasonal amplitude, frequency of fluctuations, or underlying noise levels. This disentangled representation allows practitioners to exert precise, fine-grained control over the generation process, enabling them to modify one aspect of the sequence without unintentionally altering others. Such capability is particularly valuable for expert-guided synthetic data augmentation, where domain knowledge can be directly incorporated into the generative process.

more, disentangled latent manipulation facilitates rigorous analysis of how individual components of the time series contribute to predictive performance, robustness, and statistical properties. By making the latent factors interpretable, this approach enhances the trustworthiness, explainability, and practical utility of synthetic sequences, allowing researchers and decision-makers to generate targeted, scenario-specific datasets for forecasting, simulation, or risk assessment tasks. Overall, this strategy represents a crucial step toward more controllable, transparent, and actionable time series augmentation in low-data regimes. Another important avenue for future research involves implementing dynamic architectural scaling within the L-GTA framework. Instead of using a fixed number of attention heads, layers, or latent dimensions in the V-MHA encoder, the architecture could be adapted automatically based on the characteristics of the dataset. For example, intrinsic measures of data scarcity, sequence complexity, or variability could guide the scaling process, determining the optimal model capacity required to capture temporal dependencies without overfitting. This approach would allow the model to allocate computational resources efficiently, scaling up when sufficient data is available to leverage more complex representations and scaling down when data is very limited to maintain stability. Dynamic architectural adaptation would enhance the robustness of L-GTA, ensuring consistent performance across diverse datasets and scarcity regimes. Moreover, it would facilitate efficient training on hardware-constrained environments, as the model could balance expressiveness with computational cost. Overall, this strategy would enable L-GTA to generalize better, generate high-quality synthetic sequences under varying conditions, and remain practically deployable across real-world scenarios where dataset size, complexity, and resource availability differ significantly. A further significant direction for extending the L-GTA framework is to enable full support for multivariate time series through cross-attention adaptation. This could be achieved by incorporating a Cross-Dimension Dependency Transformer within the encoder, which explicitly models inter-variable correlations while maintaining temporal coherence. By simultaneously capturing dependencies across multiple related variables, the model can generate synthetic sequences that accurately reflect the joint dynamics present in the original data. Such capability is especially valuable in complex domains where the behavior of a system is influenced by the interaction of several factors, including finance, climate science, healthcare, and industrial monitoring. For instance, in financial markets, the movements of multiple assets are often correlated, and realistic synthetic sequences must preserve these relationships to be useful for risk assessment or portfolio simulation. Similarly, in healthcare, vital signs or lab measurements are interdependent, and accurate multivariate augmentation can support predic-

tive modeling and scenario simulation. By modeling both temporal and cross-variable dependencies, Multivariate Cross-Attention Adaptation would enhance the realism, statistical fidelity, and practical applicability of synthetic sequences generated by L-GTA, making the model more reliable for complex, high-dimensional time series datasets.

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CODE AVAILABILITY

The complete implementation of the Latent Generative Transformer Augmentation (L-GTA) model, including data preprocessing scripts, model training code, and evaluation notebooks, is publicly available on GitHub. Researchers and practitioners can access the repository for reproducibility, further experiments, or adaptation to other time series domains. The GitHub repository is at: <https://github.com/abdulmoiz65315-blip/L-GTA-Project>.

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