
Time-o1: Time-Series Forecasting Needs Transformed Label Alignment

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Abstract

Training time-series forecasting models poses unique challenges in loss function design. Most existing approaches adopt temporal mean squared error, but this study reveals two critical limitations: **① it ignores the presence of label autocorrelation**, which biases it from the true label sequence likelihood; **② it involves excessive number of tasks**, which complicates optimization, especially for long-term forecasting. To address these issues, we introduce Time-o1, a transform-enhanced loss function for **time-series forecasting**. The central idea is to transform the label sequence into decorrelated components with discriminated significance. Models are then trained to align the most significant components, thereby effectively mitigating label autocorrelation and reducing task amount. Experiments demonstrate that Time-o1 achieves state-of-the-art performance and is compatible with various forecast models. Code is available at <https://github.com/Master-PLC/Time-o1>.

1 Introduction

Time-series forecasting involves predicting future data from historical observations [62, 24] and has been applied across diverse domains, such as air quality prediction in meteorology [29], user behavior analysis in e-commerce [3], and process monitoring in manufacturing [49, 52]. To build effective forecasting models, two questions warrant investigation: (1) *How to design a neural network architecture to encode historical observations, and* (2) *How to devise a loss function to train the neural network*. Both are critical for forecast model performance.

Recent research has primarily focused on developing neural network architectures [57, 61]. The key challenge lies in exploiting the autocorrelation in history sequences. To this end, various architectures have been proposed [25, 41, 53, 31]. Current progress centers on a debate between Transformers and simple linear models. Transformers, equipped with self-attention mechanisms, offer superior scalability [28, 35, 30]. In contrast, linear models, which encapsulate temporal dynamics using linear layers, are straightforward to implement and demonstrate strong performance [67, 44, 65, 63]. These advancements showcase the rapid evolution in neural architecture design for time-series forecasting.

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In contrast, the design of loss functions has received less attention [51, 40, 23]. Most studies adopt the temporal mean squared error (TMSE) as the loss function, which calculates the step-wise difference between the forecast and label sequences [28, 35]. While it is effective in various scenarios, it exhibits two limitations in time-series forecasting: **① it ignores the presence of label autocorrelation**, treating each label step as independent, which renders it biased from the true likelihood of the label sequence [51]; **② it involves excessive number of tasks**, where the task amount corresponds to the forecast horizon, which complicates optimization especially in long-term forecast scenarios [69].

To handle these challenges, we propose a transform-enhanced loss function for **time**-series forecasting (Time-o1). The key idea is to transform the label sequence into decorrelated components ranked by significance. By aligning the most significant decorrelated components, Time-o1 mitigates label autocorrelation and reduces the number of tasks. Our main contributions are summarized as follows:

- We formulate two critical challenges in designing loss functions for time-series forecasting: the label autocorrelation that induces bias, and the excessive number of tasks that impedes optimization.
- We propose Time-o1, a novel loss function for training time-series forecast models. It transforms label and forecast sequences into decorrelated components ranked by significance and subsequently align them, which effectively addresses challenges ①-② with theoretical guarantees.
- We validate the efficacy of Time-o1 through extensive experiments, where Time-o1 consistently outperforms existing loss functions and enhances the performance of various forecast models.

2 Preliminaries

This paper focuses on the time-series forecasting problem [39, 56]. In general, we adhere to standard notational conventions: uppercase bold letters (*e.g.*, \mathbf{X}) denote matrices, lowercase bold letters (*e.g.*, \mathbf{x}) denote vectors, and lowercase normal letters (*e.g.*, x) denote scalars. Since the autocorrelation property central to our analysis manifests independently within each variate, we adopt the univariate setting for problem formulation [35], which generalizes naturally to the multivariate setting.

A time series, denoted by $s = \{s_1, \dots, s_M\} \in \mathbb{R}^M$, consists of a sequence of chronologically ordered observations. At any time step n , the history sequence is represented by $\mathbf{x} = [s_{n-H+1}, \dots, s_n] \in \mathbb{R}^H$, and the corresponding label sequence is $\mathbf{y} = [s_{n+1}, \dots, s_{n+T}] \in \mathbb{R}^T$, where H denotes the history length and T is the forecast horizon. The goal of time-series forecasting is to learn a model $g : \mathbb{R}^H \rightarrow \mathbb{R}^T$ that produces a forecast sequence $\hat{\mathbf{y}}$ closely matching the ground truth label sequence.

There are two aspects to building forecast models: (1) neural network architectures that effectively encode history sequences, and (2) loss functions for training these neural networks. While **this paper focuses on the loss function**, we provide a brief review of both aspects for contextualization.

2.1 Model architectures for time-series forecasting

Neural networks are widely employed to encode history sequences [32, 60] due to their ability to automatically model feature interactions and capture complex nonlinear autocorrelation [31, 12, 11]. Notable examples include recurrent neural networks (*e.g.*, S4 [10], Mamba [9], P-sLSTM [16]), convolutional neural networks (*e.g.*, SCINet [27], TimesNet [58], MICN [54]), and graph neural networks (*e.g.*, MTGNN [34], StemGNN [2]), each tailored to encode the autocorrelations within input sequences. The current progress centers on comparisons between Transformer-based and linear architectures. Transformers (*e.g.*, PatchTST [35], iTransformer [28], FreeFormer [66]) exhibit substantial scalability with increasing data size but entail high computational costs. In contrast, linear architectures (*e.g.*, DLinear [67], RLinear [44], OLinear [65], TimeBase [13]) are generally more efficient but less scalable with larger datasets and struggle to handle varying input lengths.

2.2 Loss functions for time-series forecasting

Modern time-series models predominantly adopt the direct forecast paradigm, generating T -step forecasts simultaneously using a multi-output head [22, 28, 67]. The standard loss function is the temporal mean squared error (TMSE) between the forecast and label sequences, given by:

$$\mathcal{L}_{\text{MSE}} = \left\| \mathbf{Y} - \hat{\mathbf{Y}} \right\|_2^2 = \sum_{n=1}^N \sum_{t=1}^T (y_{n,t} - \hat{y}_{n,t})^2, \quad (1)$$

where N is the number of samples. \mathcal{L}_{MSE} is widespread in recent studies (e.g., FreTS [64], FredFormer [37], iTransformer [28], DUET [41]); however, it proves biased in the presence of label autocorrelation [51]. To address this bias, one line of works performs shape alignment between the forecast and label sequences (e.g., Soft-DTW [4], Dilate [18], and STRIPE [19]). While these methods heuristically exploit label autocorrelation, they lack theoretical guarantees regarding unbiasedness and empirical evidence of improved performance [18]. A more recent and notable approach aligns the label and forecast sequence in the frequency domain [51, 23]; this strategy offers theoretical guarantees for bias reduction [51] and empirical improvements across scenarios [55, 20, 70].

3 Methodology

3.1 Motivation

The design of loss function is pivotal in training forecast models. Most previous studies employ \mathcal{L}_{MSE} in (1) as the default loss function [28, 35, 65]. However, it suffers from two limitations stemming from the inherent properties of time series. **① It ignores the presence of label autocorrelation.** Specifically, each observation in time-series is dependent on its past values [67]; this leads to label autocorrelation, i.e., different steps in the label sequence are correlated. However, \mathcal{L}_{MSE} assumes each label step is independent, which disregards label autocorrelation and thus yields a biased loss function, as formulated in Theorem 3.1. **② It involves excessive number of tasks.** Specifically, the number of forecast tasks in \mathcal{L}_{MSE} corresponds directly to the forecast horizon T . While large forecast horizons are crucial for applications such as manufacturing (requiring long-horizon planning [50, 48]) and transportation (facilitating proactive traffic control [68, 33]), they introduce optimization challenges, e.g., gradient conflicts [69, 26], which impedes convergence and leads to suboptimal performance.

Theorem 3.1 (Autocorrelation bias). *Given a univariate label sequence $\mathbf{y} \in \mathbb{R}^T$ where $\Sigma \in \mathbb{R}^{T \times T}$ denotes the step-wise correlation coefficient, the loss function \mathcal{L}_{MSE} in (1) is biased from the true negative log-likelihood of the label sequence, which is given by:*

$$\text{Bias} = \|\mathbf{y} - \hat{\mathbf{y}}\|_{\Sigma^{-1}}^2 - \|\mathbf{y} - \hat{\mathbf{y}}\|^2 - \frac{1}{2} \log |\Sigma|. \quad (2)$$

where $\|\mathbf{v}\|_{\Sigma^{-1}}^2 = \mathbf{v}^\top \Sigma^{-1} \mathbf{v}$. The bias vanishes if different steps in \mathbf{y} are decorrelated.³

Designing a loss function to handle the two limitations is challenging. Our previous work [51] proposes a frequency-domain loss, which transforms the label and forecast sequences into frequency components and then aligns them. It is motivated by Theorem 3.1: bias vanishes if different components are decorrelated. However, the decorrelation of frequency components holds only when the forecast horizon $T \rightarrow \infty$ (see Theorem 3.3 in [51]). In real-world settings with a finite horizon, frequency components remain correlated, rendering FreDF ineffective to fully eliminate bias. Moreover, optimization difficulty remains, since transforming to the frequency domain retains the label length. *Consequently, FreDF does not fully address the limitations ①-② discussed in this paper.*

Given the significance of loss function in training forecast models and the limitations of existing methods, it is compelling to develop an innovative loss function to address the limitations and advance forecast performance. Concretely, two questions warrant investigation. *How to devise a loss function to eliminate autocorrelation bias and reduce task amount? Does it improve forecast performance?*

3.2 Transforming label sequence with optimized projection matrix

In this section, we present a method for transforming label sequences into latent components to eliminate autocorrelation and distinguish significant components. Suppose $\mathbf{Y} \in \mathbb{R}^{N \times T}$ contains univariate label sequences of N samples, $\mathbf{P} = [\mathbf{p}_1, \mathbf{p}_2, \dots, \mathbf{p}_K]$ is the projection matrix; the components are produced as $\mathbf{Z} = \mathbf{Y}\mathbf{P}$. The target is for \mathbf{Z} to be decorrelated and ranked by significance. For example, FreDF specifies \mathbf{P} as a Fourier matrix, which does not adapt to specific data properties and thus fails to decorrelate the components and distinguish the significant components⁴.

³The pioneering work [51] identifies the bias under the first-order Markov assumption on the label sequence. This study generalizes this bias without the first-order Markov assumption.

⁴In the multivariate case, different variates can be treated separately to produce decorrelated components.

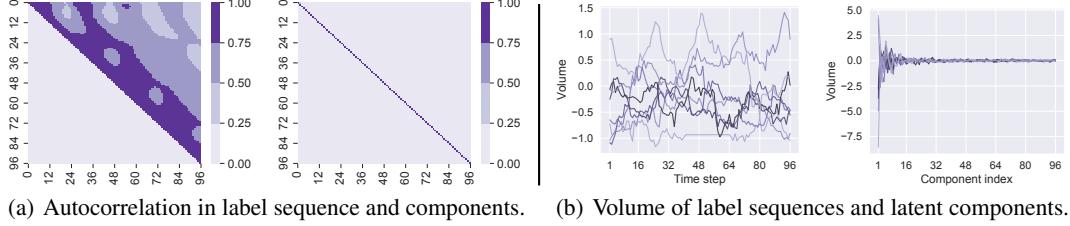


Figure 1: The autocorrelations and volumes in the label sequence \mathbf{Y} and latent components \mathbf{Z} .

A natural approach to obtaining \mathbf{P} with the desired properties is constructing optimization problem with constraints. Specifically, to find the k -th component, the projection vector \mathbf{p}_k^* can be defined as:

$$\begin{aligned} \mathbf{p}_k^* &= \operatorname{argmax}_{\mathbf{p}_k} \quad (\mathbf{Y}\mathbf{p}_k)^\top (\mathbf{Y}\mathbf{p}_k) \\ \text{subject to} \quad &\begin{cases} \|\mathbf{p}_k\|^2 = 1 \\ \mathbf{p}_k^\top \mathbf{p}_{k'} = 0, \forall k' < k \quad \text{if } k > 1 \end{cases} \end{aligned} \quad (3)$$

where $\mathbf{z}_k = \mathbf{Y}\mathbf{p}_k$ is the k -th component, the normalization constraint $\|\mathbf{p}_k\|^2 = 1$ is imposed to avoid trivial solution: $\mathbf{p}_k \rightarrow \infty$. The optimization target is to maximize the variance of \mathbf{z}_k , which is equivalent to maximizing its significance, as components with larger variance contain richer information. For $k > 1$, the projection axis is required to be orthogonal to the previous axes to avoid redundancy. By solving the optimizations above from $k = 1$ to $K \leq T$ sequentially, we obtain the projection matrix $\mathbf{P}^* = [\mathbf{p}_1^*, \dots, \mathbf{p}_K^*]$. The components are then produced as $\mathbf{Z} = \mathbf{Y}\mathbf{P}^*$.

Lemma 3.2 (Decorrelated components). *Suppose $\mathbf{Y} \in \mathbb{R}^{N \times T}$ contains normalized label sequences for N samples, $\mathbf{Z} = [\mathbf{z}_1, \dots, \mathbf{z}_K]$ are the obtained components; for any $k \neq k'$, we have $\mathbf{z}_k^\top \mathbf{z}_{k'} = 0$.*

Lemma 3.3. *The projection matrix \mathbf{P}^* can be obtained via singular value decomposition (SVD): $\mathbf{Y} = \mathbf{U}\Lambda(\mathbf{P}^*)^\top$, where $\mathbf{U} \in \mathbb{R}^{N \times N}$ and $\mathbf{P}^* \in \mathbb{R}^{K \times K}$ consist of singular vectors, and the diagonal of $\Lambda \in \mathbb{R}^{N \times K}$ consists of singular values.*

Theoretical Justification. By Theorem 3.1, the autocorrelation bias vanishes as the label correlations are eliminated. Since the obtained components \mathbf{Z} are decorrelated (Lemma 3.2), applying step-wise difference to align them suffers from little autocorrelation bias. Moreover, component significance decreases from \mathbf{z}_1 to \mathbf{z}_K as they are derived under sequentially added constraints. Furthermore, \mathbf{P}^* can be computed via SVD (Lemma 3.3), offering an efficient strategy to obtain \mathbf{P}^* .

Case study. To showcase the implications of the obtained components, a case study was conducted on the ETTh1 dataset. Implementation details are provided in Appendix A. The results are illustrated in Fig. 1, with key observations summarized as follows:

- **Decorrelation property:** Fig. 1 (a) compares the autocorrelation volume in the label sequence and the transformed components obtained by (3). In the left panel, the value at row i and column j represents the correlation between the i -th and j -th steps in the label sequence. A large number of non-diagonal elements exhibit substantial values, with approximately 50.5% exceeding 0.25, indicating significant label autocorrelation. In contrast, the right panel shows negligible values for the non-diagonal elements. This demonstrates that transforming the label sequence into components effectively eliminates correlation, which empirically validates Lemma 3.2.
- **Significance discrimination:** Fig. 1 (b) compares the variance of the label sequence and the transformed components in (3). In the left panel, the variance of the label sequence is almost uniform across different steps (ranging from -1.5 to 1.5), indicating that different steps contribute similarly to the overall information and are almost equally significant. In the right panel, a small number of components has large variance. This demonstrates that the transform yields components with ranked significance. As a result, one can balance minor information loss with substantial decreases in optimization complexity by concentrating learning on the most significant components.

The transformation is highly inspired by principal component analysis (PCA) [36]. However, one key distinction warrants emphasis. Existing works dominantly employ principal component analysis

on *input features* for obtaining informative representations [8, 6], in contrast, we adapt it to *label sequence*, specifically aiming to reduce autocorrelation bias and simplify optimization for time-series forecasting. To our knowledge, this remains a technically innovative strategy.

3.3 Model implementation

In this section, we present the implementation details of Time-o1. The approach centers on extracting the latent components from the label sequence, then optimizing the forecast model using the most significant components.

Given N history sequences $\mathbf{X} \in \mathbb{R}^{N \times H}$ and label sequences $\mathbf{Y} \in \mathbb{R}^{N \times T}$, the forecast model generates forecast sequences $\hat{\mathbf{Y}} = g(\mathbf{X})$. In line with prior practices [28, 67, 37], we standardize \mathbf{Y} (step 1), which is a prerequisite for ensuring the decorrelation of the resulting components (see Lemma 3.2). Next, following Lemma 3.3, we compute the optimal projection matrix \mathbf{P}^* by applying SVD to \mathbf{Y} , retaining only the K right singular vectors corresponding to the largest singular values (steps 2-3). Subsequently, both \mathbf{Y} and $\hat{\mathbf{Y}}$ are projected into the latent component space (step 4). In this space, significance is strictly ordered: the first column captures the greatest significance (variance), which successively diminishes across subsequent columns.

Afterwards, we compute the transformed loss to align \mathbf{Y} and $\hat{\mathbf{Y}}$ in the transformed space (step 5):

$$\mathcal{L}_{\text{ortho},\gamma} := \|\mathbf{Z} - \hat{\mathbf{Z}}\|_1, \quad (4)$$

where γ controls the ratio of components retained, such that $K = \text{round}(\gamma \cdot T)$; $\|\cdot\|_1$ computes the sum of element-wise absolute differences. Notably, we use the ℓ_1 norm instead of the squared norm following [51], since different latent components vary greatly in scale (see Fig. 1), which makes the squared norm unstable. The ℓ_1 norm provides a more stable and robust optimization landscape.

Finally, we fuse the two loss functions, with $0 \leq \alpha \leq 1$ controlling the relative contribution (step 7):

$$\mathcal{L}_{\alpha,\gamma} := \alpha \cdot \mathcal{L}_{\text{ortho},\gamma} + (1 - \alpha) \cdot \mathcal{L}_{\text{MSE}}. \quad (5)$$

By transforming both forecasts and labels into decorrelated components, Time-o1 effectively reduces autocorrelation bias. By focusing exclusively on the most significant components, Time-o1 reduces optimization difficulty with minimal information loss. Time-o1 is model-agnostic, offering practitioners the flexibility to employ the most suitable forecast model for each specific scenario.

4 Experiments

To demonstrate the efficacy of Time-o1, there are six aspects empirically investigated:

1. **Performance:** *Does Time-o1 work?* We compare Time-o1 with state-of-the-art baselines using public datasets on long-term forecasting in Section 4.2 and short-term forecasting tasks in Appendix E.1. Moreover, we compare Time-o1 with other loss functions in Section 4.3.
2. **Gain:** *How does it work?* Section 4.4 offers an ablative study to dissect the contributions of the individual factors of Time-o1, elucidating their roles in enhancing forecast accuracy.
3. **Generality:** *Does it support other forecast models?* Section 4.5 verifies the adaptability of Time-o1 across different forecast models, with additional results in Appendix E.4.
4. **Flexibility:** *Does it support alternative transformations?* Section 4.5 also investigates generating latent components with other transformations to showcase flexibility of implementation.
5. **Sensitivity:** *Does it require careful fine-tuning?* Section 4.6 presents a sensitivity analysis of the hyperparameter α , where Time-o1 maintains efficacy across a broad range of parameter values.
6. **Efficiency:** *Is it efficient?* Section D shows the running time of Time-o1 in diverse settings.

Table 1: Long-term forecasting performance.

Models	Time-o1 (Ours)	Fredformer (2024)	iTransformer (2024)	FreTS (2023)	TimesNet (2023)	MICN (2023)	TiDE (2023)	DLinear (2023)	FEDformer (2022)	Autoformer (2021)	Transformer (2017)	
Metrics	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE
ETTm1	0.380 0.393	<u>0.387</u> <u>0.398</u>	0.411	0.414	0.414	0.421	0.438	0.430	0.396	0.421	0.413	0.407
ETTm2	0.272 0.317	<u>0.280</u> <u>0.324</u>	0.295	0.336	0.316	0.365	0.302	0.334	0.308	0.364	0.286	0.328
ETTh1	0.431 0.429	<u>0.447</u> <u>0.434</u>	0.452	0.448	0.489	0.474	0.472	0.463	0.533	0.519	0.448	0.435
ETTh2	0.359 0.388	<u>0.377</u>	0.402	0.386	0.407	0.524	0.496	0.409	0.420	0.620	0.546	0.378
ECL	0.170 0.260	0.191	0.284	<u>0.179</u> <u>0.270</u>	0.199	0.288	0.212	0.306	0.192	0.302	0.215	0.292
Traffic	0.419 0.280	0.486	0.336	<u>0.426</u> <u>0.285</u>	0.538	0.330	0.631	0.338	0.529	0.312	0.624	0.373
Weather	0.241 0.280	0.261	<u>0.282</u>	0.269	0.289	<u>0.249</u>	0.293	0.271	0.295	0.264	0.321	0.272
PEMS03	0.097 0.208	0.146	0.260	0.122	0.233	0.149	0.261	0.126	0.230	<u>0.106</u> <u>0.223</u>	0.316	0.370
PEMS08	0.141 0.237	0.171	0.271	<u>0.149</u> <u>0.247</u>	0.174	0.275	0.152	0.243	0.153	0.258	0.318	0.378
											0.249	0.332
											0.422	0.456
											0.240	0.261

Note: We fix the input length as 96 following [28]. **Bold** and underlined denote best and second-best results, respectively. Avg indicates average results over forecast horizons: T=96, 192, 336 and 720. Time-o1 employs the top-performing baseline on each dataset as its underlying forecast model.

4.1 Setup

Datasets. In this work, we conduct experiments on ETT (4 subsets), ECL, Traffic, Weather, and PEMS [28] for long-term forecasting task, and M4 for short-term forecasting task [58]. All datasets are split chronologically into training, validation, and testing sets following their official settings.

Baselines. We compare Time-o1 with a range of established models, including Transformer [45], Autoformer [59], FEDformer [71], iTransformer [28], Fredformer [37], DLinear [67], TiDE [5], FreTS [64], TimesNet [58], and MICN [54]. As a loss function, Time-o1 is model-agnostic and can be integrated with any model architecture. By default, Time-o1 employs the best-performing baseline model on each dataset as its underlying model architecture for fair comparison.

Implementation. The baseline models are reproduced using the scripts provided by Fredformer [37]. All baseline models are trained using the Adam [14] optimizer to minimize \mathcal{L}_{MSE} in (1). Following the prestigious benchmark [38], the dropping-last trick is disabled during the test phase. When integrating Time-o1 to enhance an established model, we adhere to the associated hyperparameter settings in the public benchmark [37, 28], only tuning α , γ and learning rate conservatively. Experiments are conducted on Intel(R) Xeon(R) Platinum 8383C CPUs and NVIDIA RTX H100 GPUs.

4.2 Overall performance

Table 1 presents the long-term forecasting results. Time-o1 consistently improves base model performance. For example, on ETTh1, it reduces Fredformer’s MSE by 0.016. Similar gains across other datasets further validate its effectiveness. These results suggest that modifying the loss function can yield improvements comparable to, or even exceeding, those from architectural advancements. We attribute this to two key aspects of Time-o1: its decorrelation property for eliminating autocorrelation bias and its discrimination on significant components for simplifying optimization.

Showcases. We visualize the forecast sequences and the generated components to showcase the improvements of Time-o1 in forecast quality. A snapshot on ETTh2 with historical window H = 96 and forecast horizon T = 336 is depicted in Fig. 2. Although the model trained using canonical DF captures general trends, its forecast struggles with large variations (e.g., peaks within steps 100-400). This reflects its difficulty in modeling significant, high-variance components. In contrast, Time-o1, by explicitly discriminating and aligning these significant components, generates a forecast that accurately captures these large variations, including the peaks within steps 100-400.

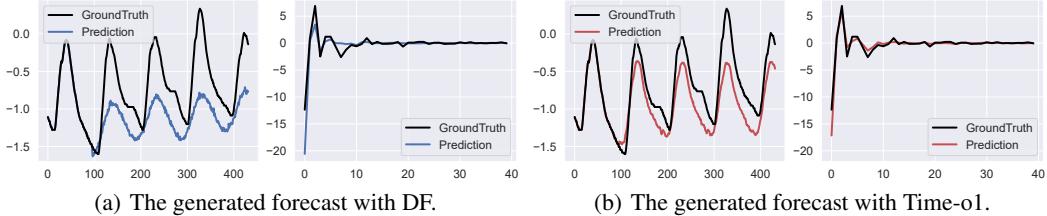


Figure 2: The visualization of label and forecast sequences generated by models trained with TMSE versus Time-o1. In both (a) and (b), the left panels display the time-domain sequences (\mathbf{Y} and $\hat{\mathbf{Y}}$), while the right panels illustrate their corresponding latent components (\mathbf{Z} and $\hat{\mathbf{Z}}$).

Table 2: Comparable results with other loss functions for time-series forecast.

Loss		Time-o1		FreDF		Koopman		Dilate		Soft-DTW		DPTA		DF	
Metrics		MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE
Fredformer	ETTm1	0.379	0.393	<u>0.384</u>	<u>0.394</u>	0.389	0.400	0.389	0.400	0.397	0.402	0.396	0.402	0.387	0.398
	ETTh1	0.431	0.429	<u>0.438</u>	<u>0.434</u>	0.452	0.443	0.453	0.442	0.460	0.449	0.460	0.449	0.447	0.434
	ECL	0.178	0.270	<u>0.179</u>	<u>0.272</u>	0.190	0.282	0.187	0.280	0.206	0.298	0.202	0.294	0.191	0.284
	Weather	0.255	0.276	<u>0.256</u>	<u>0.277</u>	0.257	0.279	0.258	0.280	0.261	0.280	0.260	0.280	0.261	0.282
iTTransformer	ETTm1	0.395	0.401	<u>0.405</u>	<u>0.405</u>	0.413	0.416	0.407	0.412	0.417	0.415	0.416	0.415	0.411	0.414
	ETTh1	0.438	0.434	<u>0.442</u>	<u>0.437</u>	0.455	0.451	0.452	0.448	0.470	0.457	0.463	0.454	0.452	0.448
	ECL	0.170	0.260	0.176	<u>0.264</u>	0.178	0.269	0.178	0.269	<u>0.175</u>	0.266	0.177	0.267	0.179	0.270
	Weather	0.251	0.272	<u>0.257</u>	<u>0.276</u>	0.289	0.313	0.286	0.309	0.292	0.316	0.291	0.313	0.269	0.289

Note: **Bold** and underlined denote best and second-best results, respectively. The reported results are averaged over forecast horizons: T=96, 192, 336 and 720.

4.3 Loss function comparison

Table 2 compares Time-o1 against other time-series loss functions: FreDF [51], Koopman [17], Dilate [18], Soft-DTW [4], and DPTA [42]. We integrate their official implementations into Fredformer and iTTransformer. Overall, shape alignment losses (Dilate, Soft-DTW, DPTA) offer little performance gain over canonical DF (using TMSE loss), consistent with the findings in [18]. This phenomenon is rationalized by the fact that they do not mitigate the label autocorrelation nor reduce task amounts for simplifying optimization. FreDF improves performance by partly addressing autocorrelation bias. However, as discussed in Section 3.1, FreDF does not fully eliminate this bias, nor does it distinguish significant components to simplify the optimization landscape. Time-o1 directly addresses these two limitations of FreDF, leading to its superior overall performance.

4.4 Ablation studies

Table 3 presents an ablation study dissecting the contributions of critical factors in Time-o1: the decorrelation property and the task reduction effect. The main findings are summarized as follows.

- Time-o1[†] improves DF by reducing the number of tasks to optimize. To this end, it employs a randomized matrix as the projection matrix to generate components and aligns only a subset of the obtained components. The involution ratio γ is finetuned on the validation set. It consistently improves over DF (e.g., -0.012 MAE on Weather). This demonstrates that reducing tasks with a minimal loss of label information can reduce optimization difficulty and improve performance.
- Time-o1[‡] improves DF by aligning decorrelated components. To this end, the loss function is calculated in (5) with $\gamma = 1$. It also outperforms DF, achieving the second-best results overall. This demonstrates aligning decorrelated label components to mitigate bias benefits forecast performance.
- Time-o1 integrates both factors above by aligning the most significant decorrelated components and achieves the best overall performance, demonstrating the synergistic effect of these two factors.

Table 3: Ablation study results.

Model	Decorrelation	Reduction	Data	T=96		T=192		T=336		T=720		Avg	
				MSE	MAE								
DF	X	X	ETTm1	0.326	0.361	0.365	0.382	0.396	0.404	0.459	0.444	0.387	0.398
			ETTh1	0.377	0.396	0.437	0.425	0.486	0.449	0.488	0.467	0.447	0.434
			ECL	0.150	0.242	0.168	0.259	0.182	0.274	0.214	0.304	0.179	0.270
			Weather	0.174	0.228	0.213	0.266	0.270	0.316	0.337	0.362	0.249	0.293
Time-o1 [†]	X	✓	ETTm1	0.338	0.366	0.369	0.383	0.397	0.403	0.458	0.441	0.391	0.398
			ETTh1	0.376	0.395	0.437	0.430	0.478	0.450	<u>0.469</u>	0.467	0.440	0.436
			ECL	0.150	0.239	0.164	0.253	0.178	0.268	0.210	0.296	0.175	0.264
			Weather	<u>0.170</u>	0.216	0.213	0.259	0.262	<u>0.300</u>	0.332	<u>0.351</u>	0.244	<u>0.281</u>
Time-o1 [‡]	✓	X	ETTm1	<u>0.324</u>	0.359	<u>0.362</u>	0.379	<u>0.390</u>	0.400	<u>0.451</u>	0.438	<u>0.382</u>	0.394
			ETTh1	<u>0.373</u>	0.395	<u>0.433</u>	0.423	<u>0.476</u>	0.445	0.474	0.463	0.439	0.431
			ECL	<u>0.147</u>	0.238	<u>0.162</u>	0.252	<u>0.174</u>	0.267	<u>0.205</u>	0.294	<u>0.172</u>	0.263
			Weather	0.172	0.220	<u>0.211</u>	0.259	<u>0.261</u>	0.301	<u>0.331</u>	0.353	<u>0.244</u>	0.283
Time-o1	✓	✓	ETTm1	0.321	0.357	0.360	0.378	0.389	0.400	0.447	0.435	0.379	0.393
			ETTh1	0.368	0.391	0.424	0.422	0.467	0.441	0.465	0.463	0.431	0.429
			ECL	0.145	0.235	0.159	0.249	0.173	0.264	0.203	0.292	0.170	0.260
			Weather	0.169	<u>0.219</u>	0.210	0.258	0.259	0.297	0.327	0.349	0.241	0.280

Note: **Bold** and underlined denote best and second-best results, respectively.

Table 4: Varying transformations results.

Transformation	ECL				Weather			
	MSE	Δ	MAE	Δ	MSE	Δ	MAE	Δ
None	0.179	-	0.270	-	0.249	-	0.293	-
RPCA	0.171	<u>4.31%↓</u>	0.261	<u>3.16%↓</u>	0.244	<u>1.78%↓</u>	0.286	<u>2.38%↓</u>
SVD	0.175	2.24%↓	0.264	2.18%↓	0.248	0.34%↓	0.290	0.93%↓
FA	0.175	2.35%↓	0.265	1.82%↓	0.245	1.35%↓	0.287	1.97%↓
Ours	0.170	4.86%↓	0.260	3.57%↓	0.241	2.94%↓	0.280	4.28%↓

Note: Δ refers to the relative error reduction compared to the baseline (None). **Bold** and underlined denote best and second-best results.

4.5 Generalization studies

In this section, we investigate the utility of Time-o1 with different transformation strategies and forecast models, to showcase the generality of Time-o1. In the bar-plots, the forecast errors are averaged over forecast lengths (96, 192, 336, 720), with error bars as 50% confidence intervals.

Varying transformations. We select alternative approaches to transform the label sequence into latent components and report the forecast performance in Table 4. The selected transformation methods include robust principal component analysis (RPCA) [1], SVD [7], and factor analysis [15]. Noting that the output of SVD yields components here, not a projection matrix as in Section 3.2. Implementation details are in Appendix C. Overall, all these transformation methods outperform canonical DF without transformation. However, the components obtained by these methods, including RPCA, cannot be guaranteed to be decorrelated. Consequently, autocorrelation bias may persist. In contrast, our approach ensures full decorrelation of the derived components (see Lemma 3.2), effectively addressing autocorrelation bias and leading to the best overall performance.

Varying forecast models. We explore the versatility of Time-o1 in augmenting representative forecast models: Fredformer [37], iTransformer [28], FrTS [64], and DLinear [67]. As illustrated in Fig. 3, Time-o1 improves forecast performance in all cases. For instance, on the Weather dataset, iTransformer and FrTS with Time-o1 achieve substantial reductions in MSE—up to 6.9% and 2.9%, respectively. Further evidence of Time-o1’s versatility can be found in Appendix E.4. These results confirm Time-o1’s potential as a plug-and-play strategy to enhance diverse forecast models.

4.6 Hyperparameter sensitivity

In this section, we examine the impact of critical hyperparameters on the performance of Time-o1. The results are presented in Table 5 and Table 6. Additional trends across different datasets and forecast lengths are provided in Appendix E.5. The primary observations are summarized as follows:

- The coefficient α determines the relative importance of the proposed transform-enhanced loss in (5). When α is set to 1, Time-o1 exclusively uses the transform-enhanced loss. Overall, increasing α from 0 to 1 leads to improved forecast accuracy, with the best results typically achieved when

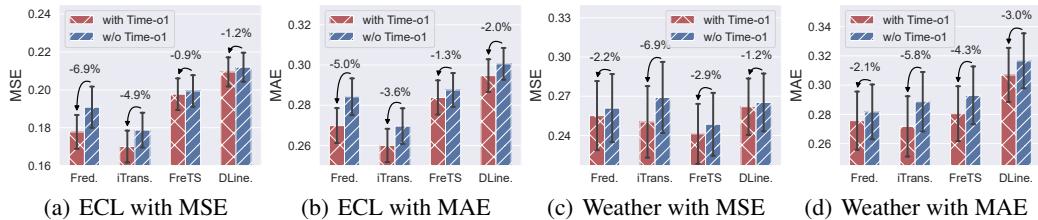


Figure 3: Improvement of Time-o1 applied to different forecast models, shown with colored bars for means over forecast lengths (96, 192, 336, 720) and error bars for 50% confidence intervals.

Table 5: Hyperparameter results on α .

α	ETTm1		ETTh2		Weather	
	MSE	MAE	MSE	MAE	MSE	MAE
0	0.3867	0.3979	0.3766	0.4019	0.2486	0.2930
0.3	0.3871	0.3983	0.3742	0.3982	0.2439	0.2851
0.5	0.3864	0.3976	0.3703	0.3964	0.2432	0.2833
0.7	0.3831	<u>0.3959</u>	<u>0.3674</u>	0.3943	<u>0.2433</u>	<u>0.2849</u>
1	<u>0.3850</u>	0.3933	0.3606	<u>0.3890</u>	0.2753	0.3209

Note: **Bold** and underlined denote best and second-best results.

Table 6: Hyperparameter results on γ .

γ	ETTm1		ETTh2		Weather	
	MSE	MAE	MSE	MAE	MSE	MAE
0.1	0.3915	0.4002	0.3816	0.4029	<u>0.2437</u>	<u>0.2845</u>
0.3	0.3849	0.3964	0.3694	0.3961	0.2424	0.2825
0.5	0.3817	0.3943	0.3651	0.3923	0.2466	0.2877
0.7	0.3798	0.3930	0.3603	0.3886	0.2443	0.2861
1	<u>0.3814</u>	<u>0.3940</u>	<u>0.3624</u>	<u>0.3903</u>	0.2491	0.2924

Note: **Bold** and underlined denote best and second-best results.

α is close to 1. The performance improvement is significant, e.g., MSE reduction on ETTh2 by 0.016, showcasing the utility of the transform-enhanced loss to improve forecast performance.

- The coefficient γ determines the ratio of retained components for training. The results demonstrate that preserving all label information ($\gamma = 1$) does not necessarily yield optimal performance. Instead, the best results are obtained at $\gamma < 1$, such as 0.7 on ETTs and 0.3 on Weather. This phenomenon can be attributed to the trade-off between information loss and optimization complexity: by focusing on the top components, optimization is simplified due to reduced task amount. Besides, since the top components contain most information, the information loss by dropping the other components is negligible. These factors synergistically contribute to improved performance.

5 Conclusion

In this study, we highlight the importance of designing loss functions for training time-series forecasting models. Two critical challenges are formulated: label autocorrelation, which induces bias, and number of tasks, which determines optimization complexity. To address these challenges, we introduce a model-agnostic loss function called Time-o1. This method transforms the label sequence into decorrelated components with discernible significance. Then, it trains forecast models to align the most significant components, which simultaneously mitigates label autocorrelation and reduces task amount. Empirically, Time-o1 improves forecast performance across diverse datasets.

Limitations & future works. In this work, we investigate the challenges of label autocorrelation and excessive number of tasks in time-series forecasting. Nevertheless, these issues also manifest in areas such as speech generation, target recognition, and dense image prediction. Applying Time-o1 in these contexts is a promising avenue for future research. Additionally, history sequence also exhibits autocorrelation and contains redundancy. Transforming inputs to derive decorrelated, compact representations could offer additional performance gains and also warrants investigation.

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References

- [1] HanQin Cai, Jian-Feng Cai, and Ke Wei. Accelerated alternating projections for robust principal component analysis. *Journal of Machine Learning Research*, 20(20):1–33, 2019.
- [2] Defu Cao, Yujing Wang, Juanyong Duan, Ce Zhang, Xia Zhu, Congrui Huang, Yunhai Tong, Bixiong Xu, Jing Bai, Jie Tong, et al. Spectral temporal graph neural network for multivariate time-series forecasting. In *Proc. Adv. Neural Inf. Process. Syst.*, volume 33, pages 17766–17778, 2020.
- [3] Zhichao Chen, Leilei Ding, Zhixuan Chu, Yucheng Qi, Jianmin Huang, and Hao Wang. Monotonic neural ordinary differential equation: Time-series forecasting for cumulative data. In *Proc. ACM Int. Conf. Inf. Knowl. Manag.*, pages 4523–4529, 2023.
- [4] Marco Cuturi and Mathieu Blondel. Soft-dtw: a differentiable loss function for time-series. In *Proc. Int. Conf. Mach. Learn.*, pages 894–903. PMLR, 2017.
- [5] Abhimanyu Das, Weihao Kong, Andrew Leach, Rajat Sen, and Rose Yu. Long-term forecasting with tide: Time-series dense encoder. *Trans. Mach. Learn. Res.*, 2023.
- [6] Urška Demšar, Paul Harris, Chris Brunsdon, A Stewart Fotheringham, and Sean McLoone. Principal component analysis on spatial data: an overview. *Ann. Assoc. Am. Geogr.*, 103(1):106–128, 2013.
- [7] Andrew Gibiansky. Cool linear algebra: Singular value decomposition. *Andrew Gibiansky Blog*, 29, 2013.
- [8] Michael Greenacre, Patrick JF Groenen, Trevor Hastie, Alfonso Iodice d’Enza, Angelos Markos, and Elena Tuzhilina. Principal component analysis. *Nat. Rev. Methods Primers*, 2(1):100, 2022.
- [9] Albert Gu and Tri Dao. Mamba: Linear-time sequence modeling with selective state spaces. In *Proc. Conf. Lang. Model.*, 2023.
- [10] Albert Gu, Karan Goel, and Christopher Re. Efficiently modeling long sequences with structured state spaces. In *Proc. Int. Conf. Learn. Represent.*, 2021.
- [11] Qihe Huang, Lei Shen, Ruixin Zhang, Jiahuan Cheng, Shouhong Ding, Zhengyang Zhou, and Yang Wang. Hdmixer: Hierarchical dependency with extendable patch for multivariate time series forecasting. In *Proc. AAAI Conf. Artif. Intell.*, volume 38, pages 12608–12616, 2024.
- [12] Qihe Huang, Zhengyang Zhou, , Yangze Li, Kuo Yang, Binwu Wang, and Yang Wang. Many minds, one goal: Time series forecasting via sub-task specialization and inter-agent cooperation. In *Proc. Adv. Neural Inf. Process. Syst.*, 2025.
- [13] Qihe Huang, Zhengyang Zhou, Kuo Yang, Zhongchao Yi, Xu Wang, and Yang Wang. Timebase: The power of minimalism in efficient long-term time series forecasting. In *Proc. Int. Conf. Mach. Learn.*, 2025.
- [14] Diederik P. Kingma and Jimmy Ba. Adam: A method for stochastic optimization. In *Proc. Int. Conf. Learn. Represent.*, pages 1–9, 2015.
- [15] Paul Kline. *An easy guide to factor analysis*. Routledge, 2014.
- [16] Yaxuan Kong, Zepu Wang, Yuqi Nie, Tian Zhou, Stefan Zohren, Yuxuan Liang, Peng Sun, and Qingsong Wen. Unlocking the power of lstm for long term time series forecasting. In *Proc. AAAI Conf. Artif. Intell.*, volume 39, pages 11968–11976, 2025.
- [17] Henning Lange, Steven L Brunton, and J Nathan Kutz. From fourier to koopman: Spectral methods for long-term time series prediction. *Journal of Machine Learning Research*, 22(41):1–38, 2021.
- [18] Vincent Le Guen and Nicolas Thome. Shape and time distortion loss for training deep time series forecasting models. In *Proc. Adv. Neural Inf. Process. Syst.*, volume 32, 2019.
- [19] Vincent Le Guen and Nicolas Thome. Probabilistic time series forecasting with shape and temporal diversity. *Proc. Adv. Neural Inf. Process. Syst.*, 33:4427–4440, 2020.
- [20] Chen Li, Hongyang Zhang, Saqlain Abbas, Chenyu Ma, Yinhao Liu, and Xiaotong Tu. Panda: Patch-aware graph network with dual alignment for time series forecasting. In *Proc. IEEE Int. Conf. Acoust. Speech Signal Process.*, pages 1–5, 2025.
- [21] Haoxuan Li, Chunyuan Zheng, Shuyi Wang, Kunhan Wu, Eric Wang, Peng Wu, Zhi Geng, Xu Chen, and Xiao-Hua Zhou. Relaxing the accurate imputation assumption in doubly robust learning for debiased collaborative filtering. In *Proc. Int. Conf. Mach. Learn.*, volume 235, pages 29448–29460, 2024.

- [22] Jianxin Li, Xiong Hui, and Wancai Zhang. Informer: Beyond efficient transformer for long sequence time-series forecasting. In *Proc. AAAI Conf. Artif. Intell.*, 2021.
- [23] Xinyu Li, Yuchen Luo, Hao Wang, Haoxuan Li, Liuhua Peng, Feng Liu, Yandong Guo, Kun Zhang, and Mingming Gong. Towards accurate time series forecasting via implicit decoding. *Proc. Adv. Neural Inf. Process. Syst.*, 2025.
- [24] Zhe Li, Xiangfei Qiu, Peng Chen, Yihang Wang, Hanyin Cheng, Yang Shu, Jilin Hu, Chenjuan Guo, Aoying Zhou, Christian S Jensen, et al. Tsfm-bench: A comprehensive and unified benchmark of foundation models for time series forecasting. In *Proc. ACM SIGKDD Int. Conf. Knowl. Discovery Data Mining*, pages 5595–5606, 2025.
- [25] Zhe Li, Xiangfei Qiu, Peng Chen, Yihang Wang, Hanyin Cheng, Yang Shu, Jilin Hu, Chenjuan Guo, Aoying Zhou, Qingsong Wen, et al. Foundts: Comprehensive and unified benchmarking of foundation models for time series forecasting. *arXiv preprint arXiv:2410.11802*, 2024.
- [26] Bo Liu, Xingchao Liu, Xiaojie Jin, Peter Stone, and Qiang Liu. Conflict-averse gradient descent for multi-task learning. *Proc. Adv. Neural Inf. Process. Syst.*, 34:18878–18890, 2021.
- [27] Minhao Liu, Ailing Zeng, Muxi Chen, Zhijian Xu, Qiuxia Lai, Lingna Ma, and Qiang Xu. Scinet: time series modeling and forecasting with sample convolution and interaction. In *Proc. Adv. Neural Inf. Process. Syst.*, 2022.
- [28] Yong Liu, Tengge Hu, Haoran Zhang, Haixu Wu, Shiyu Wang, Lintao Ma, and Mingsheng Long. itransformer: Inverted transformers are effective for time series forecasting. In *Proc. Int. Conf. Learn. Represent.*, 2024.
- [29] Jiaming Ma, Zhiqing Cui, Binwu Wang, Pengkun Wang, Zhengyang Zhou, Zhe Zhao, and Yang Wang. Causal learning meet covariates: Empowering lightweight and effective nationwide air quality forecasting. *Proc. Int. Joint Conf. Artif. Intell.*, 2025.
- [30] Jiaming Ma, Binwu Wang, Qihe Huang, Guanjun Wang, Pengkun Wang, Zhengyang Zhou, and Yang Wang. Mofo: Empowering long-term time series forecasting with periodic pattern modeling. In *Proc. Adv. Neural Inf. Process. Syst.*, 2025.
- [31] Jiaming Ma, Binwu Wang, Guanjun Wang, Kuo Yang, Zhengyang Zhou, Pengkun Wang, Xu Wang, and Yang Wang. Less but more: Linear adaptive graph learning empowering spatiotemporal forecasting. In *Proc. Adv. Neural Inf. Process. Syst.*, 2025.
- [32] Jiaming Ma, Binwu Wang, Pengkun Wang, Zhengyang Zhou, Xu Wang, and Yang Wang. Bist: A lightweight and efficient bi-directional model for spatiotemporal prediction. *Proc. VLDB Endow.*, 18(6):1663–1676, 2025.
- [33] Jiaming Ma, Binwu Wang, Pengkun Wang, Zhengyang Zhou, Yudong Zhang, Xu Wang, and Yang Wang. Mobimixer: A multi-scale spatiotemporal mixing model for mobile traffic prediction. *IEEE Trans. Mob. Comput.*, 2025.
- [34] Gonzalo Mateos, Santiago Segarra, Antonio G. Marques, and Alejandro Ribeiro. Connecting the dots: Identifying network structure via graph signal processing. *IEEE Signal Process. Mag.*, 36(3):16–43, 2019.
- [35] Yuqi Nie, Nam H Nguyen, Phanwadee Sinthong, and Jayant Kalagnanam. A time series is worth 64 words: Long-term forecasting with transformers. In *Proc. Int. Conf. Learn. Represent.*, 2023.
- [36] Karl Pearson. Principal components analysis. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 6(2):559, 1901.
- [37] Xihao Piao, Zheng Chen, Taichi Murayama, Yasuko Matsubara, and Yasushi Sakurai. Fredformer: Frequency debiased transformer for time series forecasting. In *Proc. ACM SIGKDD Int. Conf. Knowl. Discovery Data Mining*, pages 2400–2410, 2024.
- [38] Xiangfei Qiu, Jilin Hu, Lekui Zhou, Xingjian Wu, Junyang Du, Buang Zhang, Chenjuan Guo, Aoying Zhou, Christian S. Jensen, Zhenli Sheng, and Bin Yang. Tfb: Towards comprehensive and fair benchmarking of time series forecasting methods. In *Proc. VLDB Endow.*, pages 2363–2377, 2024.
- [39] Xiangfei Qiu, Xiwen Li, Ruiyang Pang, Zhicheng Pan, Xingjian Wu, Liu Yang, Jilin Hu, Yang Shu, Xuesong Lu, Chengcheng Yang, Chenjuan Guo, Aoying Zhou, Christian S. Jensen, and Bin Yang. Easymore: Time series forecasting made easy. In *Proc. IEEE Int. Conf. Data Eng.*, 2025.

- [40] Xiangfei Qiu, Xingjian Wu, Hanyin Cheng, Xvyuan Liu, Chenjuan Guo, Jilin Hu, and Bin Yang. Dbloss: Decomposition-based loss function for time series forecasting. *Proc. Adv. Neural Inf. Process. Syst.*, 2025.
- [41] Xiangfei Qiu, Xingjian Wu, Yan Lin, Chenjuan Guo, Jilin Hu, and Bin Yang. Duet: Dual clustering enhanced multivariate time series forecasting. In *Proc. ACM SIGKDD Int. Conf. Knowl. Discovery Data Mining*, pages 1185–1196, 2025.
- [42] Hiroaki Sakoe and Seibi Chiba. Dynamic programming algorithm optimization for spoken word recognition. *IEEE Trans. Signal Process.*, 26(1):43–49, 2003.
- [43] Gilbert Strang. *Introduction to linear algebra*. SIAM, 2016.
- [44] William Toner and Luke Nicholas Darlow. An analysis of linear time series forecasting models. In *Proc. Int. Conf. Mach. Learn.*, pages 48404–48427. PMLR, 2024.
- [45] Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N Gomez, Łukasz Kaiser, and Illia Polosukhin. Attention is all you need. In *Proc. Adv. Neural Inf. Process. Syst.*, 2017.
- [46] Hao Wang, Zhichao Chen, Jiajun Fan, Haoxuan Li, Tianqiao Liu, Weiming Liu, Quanyu Dai, Yichao Wang, Zhenhua Dong, and Ruiming Tang. Optimal transport for treatment effect estimation. In *Proc. Adv. Neural Inf. Process. Syst.*, volume 36, pages 5404–5418, 2023.
- [47] Hao Wang, Zhichao Chen, Zhaoran Liu, Xu Chen, Haoxuan Li, and Zhouchen Lin. Proximity matters: Local proximity enhanced balancing for treatment effect estimation. *Proc. ACM SIGKDD Int. Conf. Knowl. Discovery Data Mining*, 2025.
- [48] Hao Wang, Zhichao Chen, Zhaoran Liu, Licheng Pan, Hu Xu, Yilin Liao, Haozhe Li, and Xinggao Liu. Spot-i: Similarity preserved optimal transport for industrial iot data imputation. *IEEE Trans. Ind. Informat.*, 20(12):14421–14429, 2024.
- [49] Hao Wang, Zhichao Chen, Yuan Shen, Hui Zheng, Degui Yang, Dangjun Zhao, and Buge Liang. Unbiased recommender learning from implicit feedback via weakly supervised learning. In *IEEE Trans. Neural Netw. Learn. Syst.*, 2025.
- [50] Hao Wang, Xinggao Liu, Zhaoran Liu, Haozhe Li, Yilin Liao, Yuxin Huang, and Zhichao Chen. Lspt-d: Local similarity preserved transport for direct industrial data imputation. *IEEE Trans. Autom. Sci. Eng.*, 22:9438–9448, 2025.
- [51] Hao Wang, Licheng Pan, Yuan Shen, Zhichao Chen, Degui Yang, Yifei Yang, Sen Zhang, Xinggao Liu, Haoxuan Li, and Dacheng Tao. Fredf: Learning to forecast in the frequency domain. In *Proc. Int. Conf. Learn. Represent.*, pages 1–9, 2025.
- [52] Hao Wang, Zhiyu Wang, Yunlong Niu, Zhaoran Liu, Haozhe Li, Yilin Liao, Yuxin Huang, and Xinggao Liu. An accurate and interpretable framework for trustworthy process monitoring. *IEEE Trans. Artif. Intell.*, 5(5):2241–2252, 2023.
- [53] Haotian Wang, Haoxuan Li, Hao Zou, Haoang Chi, Long Lan, Wanrong Huang, and Wenjing Yang. Effective and efficient time-varying counterfactual prediction with state-space models. In *Proc. Int. Conf. Learn. Represent.*, 2025.
- [54] Huiqiang Wang, Jian Peng, Feihu Huang, Jince Wang, Junhui Chen, and Yifei Xiao. Micn: Multi-scale local and global context modeling for long-term series forecasting. In *Proc. Int. Conf. Learn. Represent.*, 2023.
- [55] Pengcheng Wang, Xiang Ma, Lizhen Cui, and Xuemei Li. Tscg: Efficient grouped channel interaction for multivariate time series forecasting. *Expert Syst. Appl.*, page 130299, 2025.
- [56] Yuxuan Wang, Haixu Wu, Jiaxiang Dong, Yong Liu, Mingsheng Long, and Jianmin Wang. Deep time series models: A comprehensive survey and benchmark. *arXiv preprint arXiv:2407.13278*, 2024.
- [57] Qingsong Wen, Tian Zhou, Chaoli Zhang, Weiqi Chen, Ziqing Ma, Junchi Yan, and Liang Sun. Transformers in time series: a survey. In *Proc. Int. Joint Conf. Artif. Intell.*, pages 6778–6786, 2023.
- [58] Haixu Wu, Tengge Hu, Yong Liu, Hang Zhou, Jianmin Wang, and Mingsheng Long. Timesnet: Temporal 2d-variation modeling for general time series analysis. In *Proc. Int. Conf. Learn. Represent.*, 2023.
- [59] Haixu Wu, Jiehui Xu, Jianmin Wang, and Mingsheng Long. Autoformer: Decomposition transformers with Auto-Correlation for long-term series forecasting. In *Proc. Adv. Neural Inf. Process. Syst.*, 2021.

- [60] Xingjian Wu, Zhengyu Li, Hanyin Cheng, Xiangfei Qiu, Jilin Hu, Chenjuan Guo, and Bin Yang. Unlocking the power of mixture-of-experts for task-aware time series analytics. *arXiv preprint arXiv:2509.22279*, 2025.
- [61] Xingjian Wu, Xiangfei Qiu, Hongfan Gao, Jilin Hu, Bin Yang, and Chenjuan Guo. K2vae: A koopman-kalman enhanced variational autoencoder for probabilistic time series forecasting. In *Proc. Int. Conf. Mach. Learn.*, 2025.
- [62] Xinle Wu, Xingjian Wu, Dalin Zhang, Miao Zhang, Chenjuan Guo, Bin Yang, and Christian S Jensen. Fully automated correlated time series forecasting in minutes. *Proc. VLDB Endow.*, 18(2):144–157, 2024.
- [63] Zhijian Xu, Ailing Zeng, and Qiang Xu. Fits: Modeling time series with $10k$ parameters. In *Proc. Int. Conf. Learn. Represent.*, 2024.
- [64] Kun Yi, Qi Zhang, Wei Fan, Shoujin Wang, Pengyang Wang, Hui He, Ning An, Defu Lian, Longbing Cao, and Zhendong Niu. Frequency-domain mlps are more effective learners in time series forecasting. In *Proc. Adv. Neural Inf. Process. Syst.*, 2023.
- [65] Wenzhen Yue, Yong Liu, Haoxuan Li, Hao Wang, Xianghua Ying, Ruohao Guo, Bowei Xing, and Ji Shi. Olinear: A linear model for time series forecasting in orthogonally transformed domain. *Proc. Adv. Neural Inf. Process. Syst.*, 2025.
- [66] Wenzhen Yue, Yong Liu, Xianghua Ying, Bowei Xing, Ruohao Guo, and Ji Shi. Freeformer: Frequency enhanced transformer for multivariate time series forecasting. In *Proc. Int. Joint Conf. Artif. Intell.*, pages 3606–3614, 2025.
- [67] Ailing Zeng, Muxi Chen, Lei Zhang, and Qiang Xu. Are transformers effective for time series forecasting? In *Proc. AAAI Conf. Artif. Intell.*, 2023.
- [68] Weijia Zhang, Le Zhang, Jindong Han, Hao Liu, Yanjie Fu, Jingbo Zhou, Yu Mei, and Hui Xiong. Irregular traffic time series forecasting based on asynchronous spatio-temporal graph convolutional networks. In *Proc. ACM SIGKDD Int. Conf. Knowl. Discovery Data Mining*, pages 4302–4313, 2024.
- [69] Yu Zhang and Qiang Yang. A survey on multi-task learning. *IEEE Trans. Knowl. Data Eng.*, 34(12):5586–5609, 2021.
- [70] Yungeng Zhang, Yuan Chang, Xiaohou Shi, Yaqi Song, Feng Wang, and Mingchuan Yang. Adapting large language models to forecast in frequency domain. In *Proc. IEEE Int. Conf. Acoust. Speech Signal Process.*, pages 1–5, 2025.
- [71] Tian Zhou, Ziqing Ma, Qingsong Wen, Xue Wang, Liang Sun, and Rong Jin. FEDformer: Frequency enhanced decomposed transformer for long-term series forecasting. In *Proc. Int. Conf. Mach. Learn.*, 2022.

A On the Implementation Details of Label Correlation Estimation

In this section, we introduce the motivation and implementation details of the label autocorrelation estimation techniques in Fig. 1. Measuring label autocorrelation $y_t \rightarrow y_{t'}$ is indeed challenging due to the presence of confounding effect [47, 46, 21]. Specifically, the fork structure $y_t \leftarrow \mathbf{x} \rightarrow y_{t'}$ introduces spurious correlations between y_t and $y_{t'}$, thereby distorting the true strength of the label autocorrelation $y_t \rightarrow y_{t'}$ of interest. This structural confounding undermines the validity of traditional measures such as Pearson correlation for quantifying label autocorrelation.

The previous work [51] employs the double machine learning (DML) method to estimate the ground-truth correlation while mitigating the influence of the fork structure. We adopt this in our experiments. DML is a statistical technique designed to estimate the causal effect of a treatment on an outcome while controlling for fork variables. Specifically, suppose we have a treatment variable \mathcal{T} , an outcome variable \mathcal{Y} , and a set of fork variables \mathcal{X} . The goal is to estimate the causal effect of \mathcal{T} on \mathcal{Y} while controlling for the influence of \mathcal{X} . To this end, DML first orthogonalizes both the treatment and outcome with respect to the fork variables. Two parametric models are employed to predict the treatment and outcome based on the fork variables. These predictions capture the impact of \mathcal{X} on \mathcal{Y} and \mathcal{T} . Subsequently, such impact of \mathcal{X} is eliminated by calculating the residuals. Finally, the DML method regresses the outcome residuals on the treatment residuals, thereby measuring the causal effect of \mathcal{T} on \mathcal{Y} while removing the influence of the fork variables.

In our experiments, we measure label autocorrelation by treating the input sequence \mathbf{x} as the fork variable and different steps of the label sequences y_t and $y_{t'}$ as the treatment and outcome variables, respectively. Then, we estimate the treatment effect of y_t on $y_{t'}$ controlling \mathbf{x} . Similarly, when measuring the correlation between different components, we use different components z_k and $z_{k'}$ as the treatment and outcome variables. Linear regression model is employed as the parametric model for both the treatment and outcome variables for efficiency, which is consistent with [51].

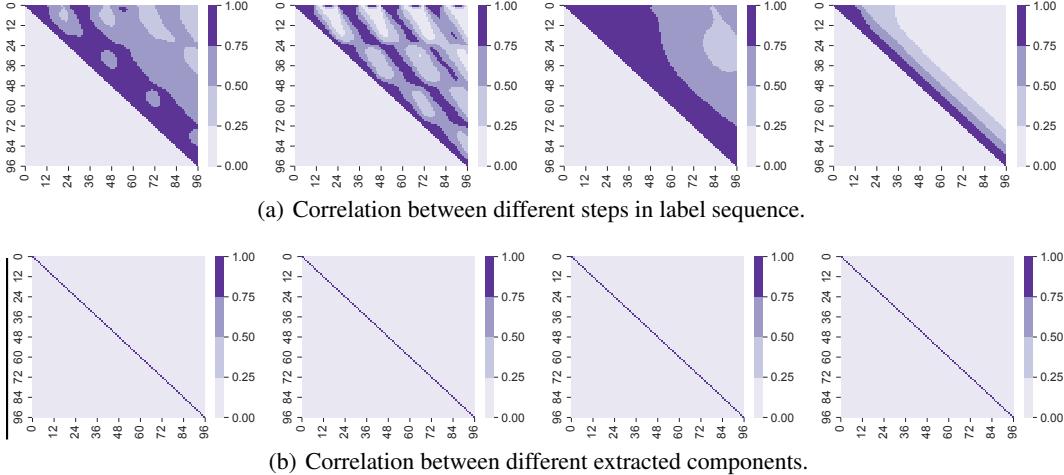


Figure 4: The label autocorrelation in the original label sequence and the extracted components. The datasets are ETTh1, ETTh2, ETTm1, and Weather from left to right. The forecast length is set to 96.

To further complement the case study in Fig. 1, we analyzed the correlation matrices of the label sequences and the extracted components across multiple datasets, with the results presented in Fig. 4. The main observations are summarized as follows.

- Panel (a) displays the correlation matrix of the label sequence, characterized by substantial non-diagonal elements, which highlight the strong autocorrelation among the labels. In contrast, panel (b) shows the correlation matrix of the extracted components, where the non-diagonal elements are nearly zero, indicating effective decorrelation.
- Compared to the results reported in [51], where some obtained components remain correlated, the non-diagonal elements in panel (b) are fully eliminated. This difference arises because the Fourier transform in [51] achieves decorrelation only when the original label sequence is nearly infinitely long ($T \rightarrow \infty$), a condition that is not met in real-world applications with finite forecast horizons.

This limitation stems from the predefined nature of the projection matrix, which lacks adaptation to the specific properties of the data. In contrast, our method ensures decorrelation by solving a constrained optimization problem, without relying on an infinitely long forecast horizon, thereby providing a more reliable approach for handling autocorrelation bias.

B Theoretical Justification

Theorem B.1 (Autocorrelation bias, Theorem 3.1 in the main text). *Given a univariate label sequence $\mathbf{y} \in \mathbb{R}^T$ where $\Sigma \in \mathbb{R}^{T \times T}$ denotes the step-wise correlation coefficient, the loss function \mathcal{L}_{MSE} in (1) is biased from the true negative log-likelihood of the label sequence, which is given by:*

$$\text{Bias} = \|\mathbf{y} - \hat{\mathbf{y}}\|_{\Sigma^{-1}}^2 - \|\mathbf{y} - \hat{\mathbf{y}}\|^2 - \frac{1}{2} \log |\Sigma|. \quad (6)$$

where $\|\mathbf{v}\|_{\Sigma^{-1}}^2 = \mathbf{v}^\top \Sigma^{-1} \mathbf{v}$. The bias vanishes if different steps in \mathbf{y} are decorrelated.⁵

Proof. The proof follows our previous work [51] but relaxes the first-order Markov assumption.

Suppose the label sequence follows a multivariate normal distribution with mean vector $\mu = \hat{\mathbf{y}}$ and covariance matrix Σ , where the off-diagonal entries are $\Sigma_{ij} = \rho_{ij}\sigma^2$ for $i \neq j$. Here, ρ_{ij} denotes the partial correlation between y_i and y_j . The log-likelihood of the label sequence \mathbf{Y} can be expressed as:

$$\log p(\mathbf{y}) = \frac{1}{2} (\text{T log}(2\pi) + \log |\Sigma| + (\mathbf{y} - \hat{\mathbf{y}})^\top \Sigma^{-1} (\mathbf{y} - \hat{\mathbf{y}})).$$

Removing the constant terms unrelated to $\hat{\mathbf{y}}$, we obtain the practical negative log-likelihood (PNLL):

$$\text{PNLL} = (\mathbf{y} - \hat{\mathbf{y}})^\top \Sigma^{-1} (\mathbf{y} - \hat{\mathbf{y}}).$$

On the other hand, the TMSE loss can be expressed as:

$$\text{TMSE} = \|\mathbf{y} - \hat{\mathbf{y}}\|_2^2 = (\mathbf{y} - \hat{\mathbf{y}})^\top \mathbf{I}^{-1} (\mathbf{y} - \hat{\mathbf{y}}).$$

where \mathbf{I} is the identity matrix. The difference between TMSE and PNLL can be expressed as:

$$\text{Bias} = \text{PNLL} - \text{TMSE} = (\mathbf{y} - \hat{\mathbf{y}})^\top \Sigma^{-1} (\mathbf{y} - \hat{\mathbf{y}}) - (\mathbf{y} - \hat{\mathbf{y}})^\top \mathbf{I} (\mathbf{y} - \hat{\mathbf{y}}),$$

which immediately vanishes if the label sequence is decorrelated, i.e., $\Sigma = \mathbf{I}$. The proof is completed. \square

Lemma B.2 (Lemma 3.3 in the main text). *The projection matrix \mathbf{P}^* can be obtained via singular value decomposition (SVD): $\mathbf{Y} = \mathbf{U}\Lambda(\mathbf{P}^*)^\top$, where $\mathbf{U} \in \mathbb{R}^{N \times N}$ and $\mathbf{P}^* \in \mathbb{R}^{K \times K}$ consist of singular vectors, and the diagonal of $\Lambda \in \mathbb{R}^{N \times K}$ consists of singular values.*

Proof. The proof is available in Section 7.3 in [43]. \square

Lemma B.3 (Decorrelated components, Lemma 3.2 in the main text). *Suppose $\mathbf{Y} \in \mathbb{R}^{N \times T}$ contains normalized label sequences for N samples, $\mathbf{Z} = [\mathbf{z}_1, \dots, \mathbf{z}_K]$ are the obtained components; for any $k \neq k'$, we have $\mathbf{z}_k^\top \mathbf{z}_{k'} = 0$.*

Proof. For any two latent components \mathbf{z}_k and $\mathbf{z}_{k'}$ with $k \neq k'$, we have:

$$\mathbf{z}_k^\top \mathbf{z}_{k'} = (\mathbf{Y}\mathbf{p}_k)^\top (\mathbf{Y}\mathbf{p}_{k'}) = \mathbf{p}_k^\top \mathbf{Y}^\top \mathbf{Y} \mathbf{p}_{k'} \quad (7)$$

Noting that \mathbf{p}_k and $\mathbf{p}_{k'}$ are eigenvectors of $\mathbf{Y}^\top \mathbf{Y}$ [43], we have

$$\mathbf{Y}^\top \mathbf{Y} \mathbf{p}_k = \lambda_k \mathbf{p}_k, \quad \mathbf{Y}^\top \mathbf{Y} \mathbf{p}_{k'} = \lambda_{k'} \mathbf{p}_{k'}, \quad (8)$$

which immediately follows by $\mathbf{z}_k^\top \mathbf{z}_{k'} = \lambda_{k'} \mathbf{p}_k^\top \mathbf{p}_{k'}$. Recalling that different projection bases are constrained to orthogonal, i.e., $\mathbf{p}_k^\top \mathbf{p}_{k'} = 0$ for $k \neq k'$, we have

$$\mathbf{z}_k^\top \mathbf{z}_{k'} = 0 \quad \text{for all } k \neq k', \quad (9)$$

which completes the proof. \square

⁵The pioneering work [51] identifies the bias under the first-order Markov assumption on the label sequence. This study generalizes this bias without the first-order Markov assumption.

C Generalized Orthogonalization and Decorrelation Methods

In this section, we introduce alternative transforms for obtaining latent components, each with distinct characteristics such as dimensionality reduction and noise isolation. A comparatively empirical study is provided in Section 4.5.

RPCA. The robust principal component analysis decomposes the data into a low-rank informative component and a sparse noise component, effectively separating structured signals from noise. Specifically, given $\mathbf{Y} \in \mathbb{R}^{N \times T}$, it is achieved by solving:

$$\min_{\mathbf{V}, \mathbf{S}} \|\mathbf{V}\|_* + \lambda \|\mathbf{S}\|_1, \quad \text{subject to } \mathbf{Y} = \mathbf{V} + \mathbf{S}, \quad (10)$$

where $\|\cdot\|_*$ is the nuclear norm, $\|\cdot\|_1$ is the element-wise ℓ_1 norm, and λ is a regularization parameter. Afterwards, it performs the principal component analysis on the obtained informative component \mathbf{V} to derive the projection matrix \mathbf{P} . The latent components are generated by $\mathbf{Z} = \mathbf{Y}\mathbf{P}$. While this approach enhances noise elimination, it does not guarantee decorrelation of the derived components, as the projection matrix \mathbf{P} is derived from \mathbf{V} instead of the original data matrix \mathbf{Y} .

SVD. The singular value decomposition provides a method to decompose the matrix into different components. Given $\mathbf{Y} \in \mathbb{R}^{N \times T}$, we have:

$$\mathbf{Y} = \mathbf{U}\Lambda\mathbf{V}^\top, \quad (11)$$

where $\mathbf{U} \in \mathbb{R}^{N \times r}$ and $\mathbf{V} \in \mathbb{R}^{T \times r}$ are singular vectors, $\Lambda \in \mathbb{R}^{r \times r}$ is diagonal with rank r . The right singular vector is used as the projection matrix, and the latent components are generated by $\mathbf{Z} = \mathbf{Y}\mathbf{V}$. One key distinction here needs to be highlighted. Unlike the workflow in the main text (Algorithm 1), the label sequence is not normalized after window generation before computing SVD here, resulting in non-decorrelated components.

FA. Factor analysis models the observed data as linear combinations of a small number of latent factors plus noise, capturing the covariance structure through these unobserved factors. Specifically, given mean-centered $\mathbf{Y} \in \mathbb{R}^{N \times T}$, the model assumes:

$$\mathbf{Y} = \mathbf{V}\mathbf{F}^\top + \mathbf{E}, \quad (12)$$

where $\mathbf{V} \in \mathbb{R}^{N \times K}$ is the factor loading matrix, K is the number of latent factors ($K \ll N$), $\mathbf{F} \in \mathbb{R}^{T \times K}$ contains the latent factor scores for each sample, and $\mathbf{E} \in \mathbb{R}^{N \times T}$ is the noise matrix. The standard assumption is that each factor $f_i \sim \mathcal{N}(0, \mathbf{I})$ and noise $e_i \sim \mathcal{N}(0, \Psi)$, where Ψ is a diagonal covariance matrix. The loadings \mathbf{V} and factor scores \mathbf{F} are typically estimated via maximum likelihood. The latent components are given by the estimated factor scores, *i.e.*, $\mathbf{Z} = \mathbf{Y}\Psi^{-1}\mathbf{F}(\mathbf{I} + \mathbf{F}^\top\Psi^{-1}\mathbf{F})^{-1} := \mathbf{Y}\mathbf{P}$ ⁶. This approach captures the covariance structure of \mathbf{Y} via a small number of factors, but does not necessarily guarantee uncorrelated or noise-isolated components.

D Complexity Analysis

In this section, we analyze the running cost of Time-o1. The core computation of Time-o1 involves (a) calculating the projection matrix \mathbf{P}^* via SVD, and (b) performing transformation on both \mathbf{Y} and $\hat{\mathbf{Y}}$ followed by calculating their point-wise MAE loss. Given the target matrix $\mathbf{Y} \in \mathbb{R}^{N \times T}$, the SVD step decomposes \mathbf{Y} with an established complexity of $\mathcal{O}(NT^2)$ (assuming $N \geq T$ and $K = T$). For the sequence transformation, each sample (row) in \mathbf{Y} is multiplied by the projection matrix $\mathbf{P}^* \in \mathbb{R}^{T \times T}$, resulting in a total complexity of $\mathcal{O}(NT^2)$. The computation of point-wise MAE loss across all samples and forecast steps is $\mathcal{O}(NT)$, which is negligible compared to the complexity of previous steps. Thus, the overall complexity per batch is dominated by the SVD and projection operations, both scaling as $\mathcal{O}(NT^2)$. The main findings from the empirical evaluations are as follows.

- Fig. 5 (a) presents the computational cost for calculating the projection matrix. Overall, it increases linearly with the sample size and quadratically with the prediction length, which aligns with the theoretical complexity. Importantly, this operation is performed only once before training begins, rendering the associated overhead acceptable.

⁶Adapted from source code of sklearn: <https://github.com/scikit-learn/scikit-learn/blob/98ed9dc73/sklearn/decomposition/>

- Fig. 5 (b) presents the computational cost for the sequence transformation. The cost increases quadratically with the prediction length, but remains below 2 ms. This cost is comparable to that of a linear projection. Furthermore, sequence transformation is not required during inference.

In conclusion, Time-o1 does not add complexity to model inference, and the additional complexity during the training stage is negligible.

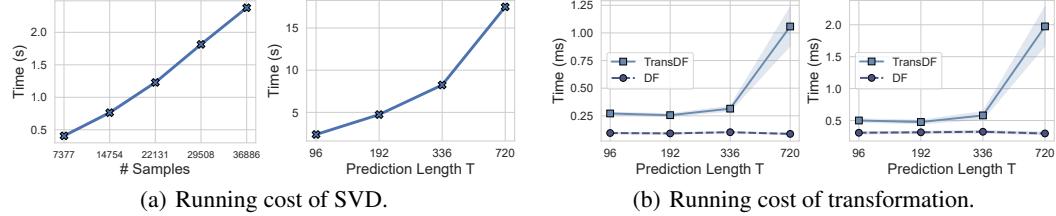


Figure 5: Running cost for projection matrix calculation (left panel with varying number of samples, right panel with varying prediction length) and sequence transformation (left panel for forward pass, right panel for backward pass, with average and shaded areas for 95% confidence intervals).

E More Experimental Results

E.1 Long-term forecast performance

Additional results on long-term forecast performance are available in Table 7.

E.2 Short-term forecast performance

Additional results on short-term forecast performance are available in Table 8, where Fredformer [37] serves as the forecast model.

E.3 Showcases

Additional results on showcases are available in Fig. 6 and Fig. 7.

E.4 Generalization studies

Additional results on varying forecast models and transformations are available in Fig. 8 and Table 9.

E.5 Hyperparameter sensitivity

Additional results on hyperparameter sensitivity are available in Fig. 9 for α and Fig. 10 for γ .

E.6 Comparison with different loss functions

Additional results on comparing different loss functions are available in Table 10.

E.7 Varying input length results

Additional results on varying input lengths are available in Table 11—complementing the fixed length of 96 used in the main text.

E.8 Random seed sensitivity

Additional results on varying random seeds are available in Table 12.

Table 7: The comprehensive results on the long-term forecasting task.

Models	Time-o1 (Ours)	Fredformer (2024)	iTransformer (2024)	FreTS (2023)	TimesNet (2023)	MICN (2023)	TiDE (2023)	DLinear (2023)	FEDformer (2022)	Autoformer (2021)	Transformer (2017)	
Metrics	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE
ETTm1	96	0.321 0.357	0.326 0.361	0.338 0.372	0.342 0.375	0.368 0.394	0.319 0.366	0.353 0.374	0.346 0.373	0.401 0.434	0.485 0.468	0.503 0.482
	192	0.360 0.378	0.365 0.382	0.382 0.396	0.385 0.400	0.406 0.409	0.364 0.395	0.391 0.393	0.380 0.390	0.415 0.446	0.504 0.482	0.807 0.664
	336	0.389 0.400	0.396 0.404	0.427 0.424	0.416 0.421	0.454 0.444	0.395 0.425	0.423 0.414	0.413 0.414	0.432 0.450	0.520 0.489	0.847 0.678
	720	0.447 0.435	0.459 0.444	0.496 0.463	0.513 0.489	0.527 0.474	0.505 0.499	0.486 0.448	0.472 0.450	0.522 0.500	0.594 0.523	1.037 0.771
	Avg	0.379 0.393	0.387 0.398	0.411 0.414	0.414 0.421	0.438 0.430	0.396 0.421	0.413 0.407	0.403 0.407	0.442 0.457	0.526 0.491	0.799 0.648
ETTm2	96	0.172 0.251	0.177 0.260	0.182 0.265	0.188 0.279	0.184 0.262	0.178 0.277	0.182 0.265	0.188 0.283	0.205 0.289	0.218 0.300	0.386 0.441
	192	0.235 0.294	0.242 0.300	0.257 0.315	0.264 0.329	0.257 0.308	0.266 0.343	0.247 0.304	0.280 0.356	0.271 0.334	0.282 0.340	1.410 0.881
	336	0.293 0.333	0.302 0.340	0.320 0.354	0.322 0.369	0.315 0.345	0.299 0.354	0.307 0.343	0.375 0.420	0.327 0.366	0.335 0.370	1.940 1.070
	720	0.388 0.389	0.399 0.397	0.423 0.411	0.489 0.482	0.452 0.421	0.489 0.482	0.408 0.398	0.526 0.508	0.428 0.425	0.423 0.420	2.914 1.276
	Avg	0.272 0.317	0.280 0.324	0.295 0.336	0.316 0.365	0.302 0.334	0.308 0.364	0.286 0.328	0.342 0.392	0.308 0.354	0.315 0.358	1.662 0.917
ETTh1	96	0.368 0.391	0.377 0.396	0.385 0.405	0.398 0.409	0.399 0.418	0.381 0.416	0.387 0.395	0.389 0.404	0.391 0.433	0.449 0.465	1.028 0.778
	192	0.424 0.422	0.437 0.425	0.440 0.437	0.451 0.442	0.452 0.451	0.497 0.489	0.439 0.425	0.442 0.440	0.418 0.448	0.459 0.469	1.010 0.789
	336	0.467 0.441	0.486 0.449	0.480 0.457	0.501 0.472	0.488 0.469	0.589 0.555	0.482 0.447	0.488 0.467	0.487 0.484	0.511 0.500	0.908 0.743
	720	0.465 0.463	0.488 0.467	0.504 0.492	0.608 0.571	0.549 0.515	0.665 0.617	0.484 0.471	0.505 0.502	0.494 0.514	0.488 0.498	0.987 0.785
	Avg	0.431 0.429	0.447 0.434	0.452 0.448	0.489 0.474	0.472 0.463	0.533 0.519	0.448 0.435	0.456 0.453	0.447 0.470	0.477 0.483	0.983 0.774
ETTh2	96	0.282 0.330	0.293 0.344	0.301 0.349	0.315 0.374	0.321 0.358	0.351 0.398	0.291 0.340	0.330 0.383	0.351 0.391	0.355 0.397	1.485 0.959
	192	0.359 0.381	0.372 0.391	0.383 0.397	0.466 0.467	0.418 0.417	0.492 0.489	0.376 0.392	0.439 0.450	0.456 0.456	0.478 0.471	4.218 1.585
	336	0.394 0.414	0.420 0.433	0.425 0.432	0.522 0.502	0.464 0.454	0.656 0.582	0.417 0.427	0.589 0.538	0.477 0.492	0.459 0.469	2.775 1.361
	720	0.400 0.427	0.421 0.439	0.436 0.448	0.792 0.643	0.434 0.450	0.981 0.718	0.429 0.446	0.757 0.626	0.522 0.505	0.499 0.502	2.274 1.257
	Avg	0.359 0.388	0.377 0.402	0.386 0.407	0.524 0.496	0.409 0.420	0.620 0.546	0.378 0.401	0.529 0.499	0.452 0.461	0.448 0.460	2.688 1.291
ECL	96	0.145 0.235	0.161 0.258	0.150 0.242	0.180 0.266	0.170 0.272	0.170 0.281	0.197 0.274	0.197 0.282	0.187 0.302	0.189 0.304	0.253 0.350
	192	0.159 0.249	0.174 0.269	0.168 0.259	0.184 0.272	0.183 0.282	0.185 0.297	0.197 0.277	0.197 0.286	0.207 0.322	0.271 0.371	0.262 0.356
	336	0.173 0.264	0.194 0.290	0.182 0.274	0.199 0.290	0.203 0.302	0.190 0.298	0.212 0.292	0.209 0.301	0.211 0.326	0.243 0.352	0.269 0.363
	720	0.203 0.292	0.235 0.319	0.214 0.304	0.234 0.322	0.294 0.366	0.221 0.329	0.254 0.325	0.245 0.334	0.253 0.361	0.295 0.388	0.277 0.365
	Avg	0.170 0.260	0.191 0.284	0.179 0.270	0.199 0.288	0.212 0.306	0.192 0.302	0.215 0.292	0.212 0.301	0.214 0.328	0.249 0.354	0.265 0.358
Traffic	96	0.393 0.265	0.461 0.327	0.397 0.271	0.531 0.323	0.590 0.316	0.498 0.298	0.646 0.386	0.649 0.397	0.588 0.367	0.575 0.356	0.689 0.396
	192	0.410 0.275	0.470 0.326	0.416 0.279	0.519 0.321	0.624 0.336	0.521 0.309	0.599 0.362	0.598 0.371	0.613 0.377	0.647 0.394	0.710 0.388
	336	0.421 0.280	0.492 0.338	0.429 0.286	0.529 0.327	0.641 0.345	0.529 0.314	0.606 0.363	0.605 0.373	0.640 0.398	0.694 0.446	0.687 0.366
	720	0.451 0.298	0.521 0.353	0.462 0.303	0.573 0.346	0.670 0.356	0.567 0.326	0.643 0.383	0.646 0.395	0.718 0.450	0.731 0.468	0.681 0.366
	Avg	0.419 0.280	0.486 0.336	0.426 0.285	0.538 0.330	0.631 0.338	0.529 0.312	0.624 0.373	0.625 0.384	0.640 0.398	0.662 0.416	0.692 0.379
Weather	96	0.169 0.219	0.180 0.220	0.171 0.210	0.174 0.228	0.183 0.229	0.179 0.244	0.192 0.232	0.194 0.253	0.235 0.310	0.233 0.306	0.423 0.448
	192	0.210 0.258	0.222 0.258	0.246 0.278	0.213 0.266	0.242 0.276	0.242 0.310	0.240 0.270	0.238 0.296	0.295 0.353	0.286 0.347	0.664 0.585
	336	0.259 0.297	0.283 0.301	0.296 0.313	0.270 0.316	0.293 0.312	0.273 0.330	0.292 0.307	0.282 0.332	0.364 0.397	0.346 0.385	0.848 0.686
	720	0.327 0.349	0.358 0.348	0.362 0.353	0.337 0.362	0.366 0.361	0.360 0.399	0.364 0.353	0.347 0.385	0.411 0.429	0.412 0.420	0.861 0.685
	Avg	0.241 0.280	0.261 0.282	0.269 0.289	0.249 0.293	0.271 0.295	0.264 0.321	0.272 0.291	0.265 0.317	0.326 0.372	0.319 0.365	0.699 0.601
PEMS03	12	0.070 0.176	0.081 0.191	0.072 0.179	0.085 0.198	0.094 0.201	0.096 0.217	0.117 0.226	0.105 0.220	0.108 0.229	0.233 0.366	0.106 0.206
	24	0.087 0.198	0.121 0.240	0.104 0.217	0.129 0.244	0.116 0.221	0.095 0.210	0.233 0.322	0.183 0.297	0.131 0.255	0.405 0.485	0.117 0.221
	36	0.105 0.219	0.180 0.292	0.137 0.251	0.173 0.286	0.134 0.237	0.107 0.223	0.379 0.418	0.258 0.361	0.159 0.285	0.327 0.415	0.127 0.233
	48	0.124 0.238	0.201 0.316	0.174 0.285	0.207 0.315	0.161 0.262	0.125 0.242	0.535 0.516	0.319 0.410	0.209 0.331	0.679 0.634	0.139 0.245
	Avg	0.097 0.208	0.146 0.260	0.122 0.233	0.149 0.261	0.126 0.230	0.106 0.223	0.316 0.370	0.216 0.322	0.152 0.275	0.411 0.475	0.122 0.226
PEMS08	12	0.081 0.183	0.091 0.199	0.084 0.187	0.096 0.205	0.111 0.208	0.161 0.274	0.121 0.233	0.113 0.225	0.163 0.258	0.232 0.334	0.204 0.232
	24	0.117 0.218	0.138 0.245	0.123 0.227	0.151 0.258	0.139 0.232	0.127 0.237	0.232 0.325	0.199 0.302	0.197 0.288	0.545 0.550	0.232 0.251
	36	0.157 0.253	0.199 0.303	0.170 0.268	0.203 0.303	0.168 0.260	0.148 0.252	0.376 0.427	0.295 0.371	0.241 0.326	0.379 0.436	0.246 0.263
	48	0.207 0.294	0.255 0.338	0.218 0.306	0.247 0.334	0.189 0.272	0.175 0.270	0.543 0.527	0.389 0.429	0.302 0.375	0.531 0.502	0.278 0.297
	Avg	0.141 0.237	0.171 0.271	0.149 0.247	0.174 0.275	0.152 0.243	0.153 0.258	0.318 0.378	0.249 0.332	0.226 0.312	0.422 0.456	0.240 0.261
1 st Count	43	42	0	1	0	0	1	1	0	0	0	0

Note: We fix the input length as 96 following [28]. **Bold** typeface highlights the top performance for each metric, while underlined text denotes the second-best results. Avg indicates the results averaged over forecasting lengths: T=96, 192, 336 and 720.

Table 8: The comprehensive results on the short-term forecasting task.

Models	Time-o1 (Ours)	Fredformer (2024)	iTransformer (2024)	FrTS (2023)	MICN (2023)	DLinear (2023)	Fedformer (2023)
Metric	SMAPE MASE OWA	SMAPE MASE OWA	SMAPE MASE OWA	SMAPE MASE OWA	SMAPE MASE OWA	SMAPE MASE OWA	SMAPE MASE OWA
Yearly	13.485 <u>3.010</u> <u>0.791</u>	<u>13.509</u> <u>3.028</u> <u>0.794</u>	13.797 3.143 0.818	13.576 3.068 0.801	14.594 3.392 0.873	14.307 3.094 0.827	13.648 3.089 0.806
Quarterly	10.105 <u>1.180</u> <u>0.889</u>	<u>10.140</u> <u>1.185</u> <u>0.893</u>	10.503 1.248 0.932	10.361 1.223 0.916	11.417 1.385 1.023	10.500 1.237 0.928	10.612 1.246 0.936
Monthly	12.649 <u>0.930</u> <u>0.875</u>	<u>12.696</u> <u>0.931</u> <u>0.878</u>	13.227 1.013 0.935	13.088 0.990 0.919	13.834 1.080 0.987	13.362 1.007 0.937	14.181 1.105 1.011
Others	4.852 3.274 1.027	4.848 <u>3.230</u> <u>1.019</u>	<u>5.101</u> <u>3.419</u> <u>1.076</u>	5.563 3.71 1.17	6.137 4.201 1.308	5.12 3.649 1.114	4.823 <u>3.243</u> <u>1.019</u>
Average	11.841 <u>1.585</u> <u>0.851</u>	<u>11.879</u> <u>1.590</u> <u>0.854</u>	12.298 1.68 0.893	12.169 1.66 0.883	13.044 1.841 0.962	12.48 1.674 0.898	12.734 1.702 0.914
1 st Count	4 4 4	0 1 1	0 0 0	0 0 0	0 0 0	0 0 0	1 0 0

Note: **Bold** typeface highlights the top performance for each metric, while underlined text denotes the second-best results. Avg indicates the results averaged over forecasting lengths: yearly, quarterly, and monthly.

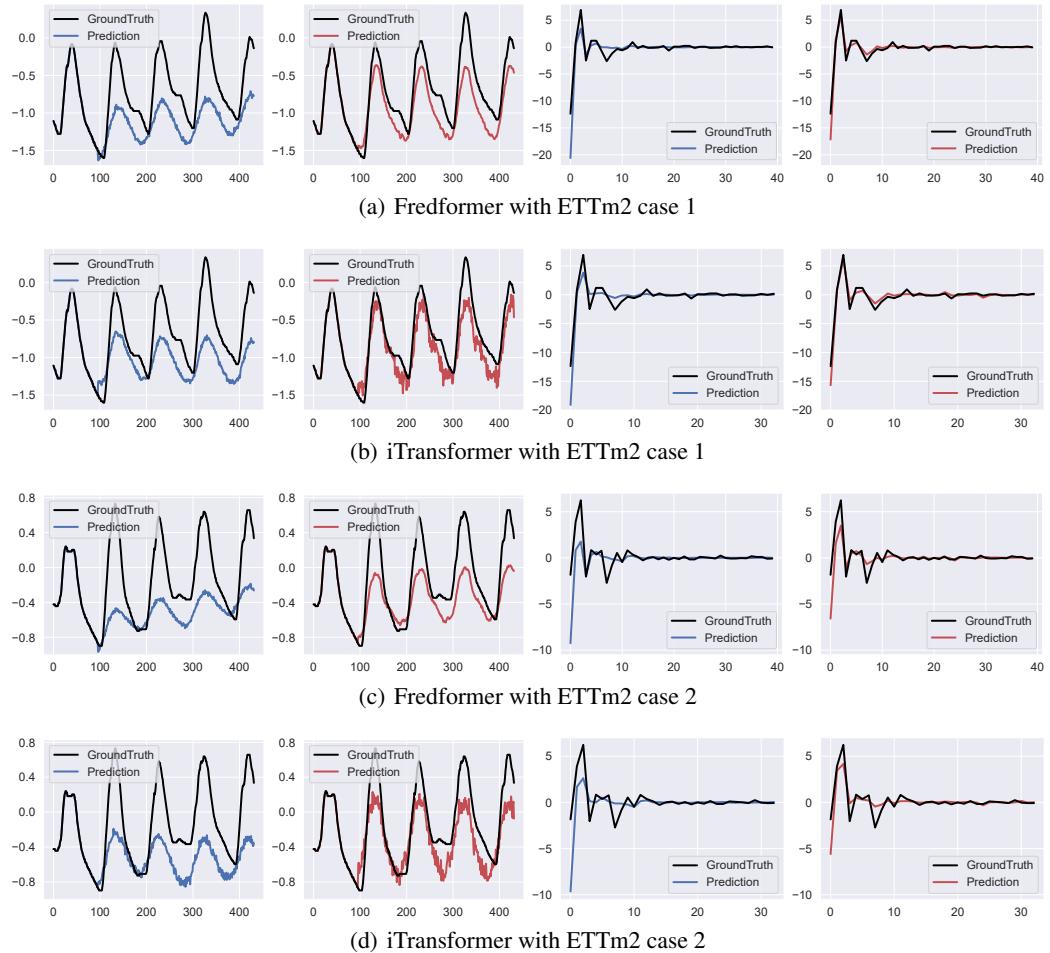


Figure 6: The forecast sequences generated with DF and Time-o1. The forecast length is set to 336 and the experiment is conducted on ETTm2.

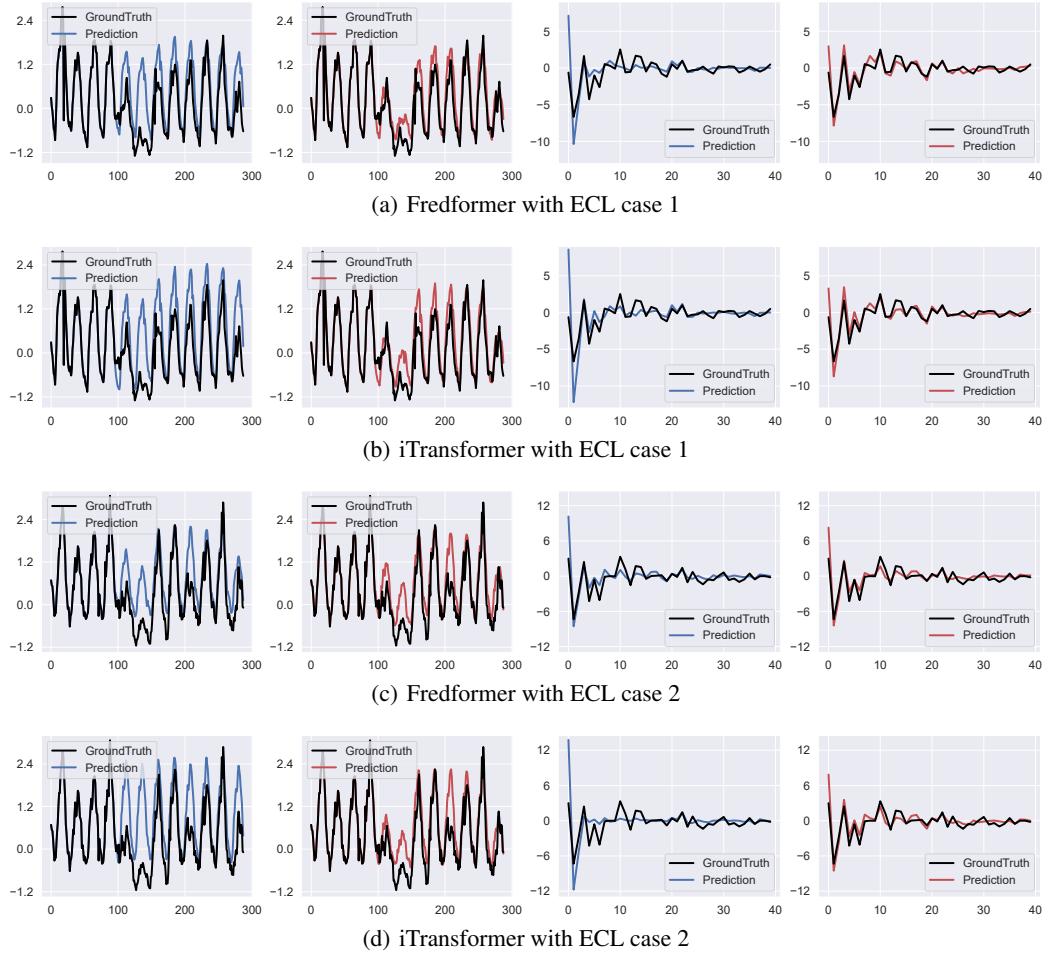


Figure 7: The forecast sequences generated with DF and Time-o1. The forecast length is set to 192 and the experiment is conducted on ECL.

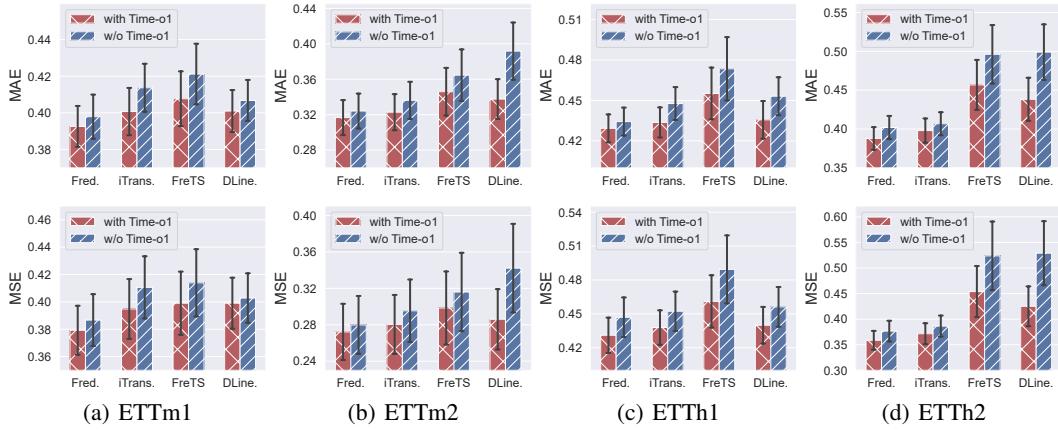


Figure 8: Performance of different forecast models with and without Time-o1. The forecast errors are averaged over forecast lengths and the error bars represent 50% confidence intervals.

Table 9: Varying transformation results.

Trans	PCA		RPCA		SVD		FA		DF		
	Metrics	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE
ECL	96	0.1449	0.2348	0.1450	0.2349	0.1450	0.2350	0.1478	0.2385	0.1500	0.2415
	192	0.1592	0.2487	0.1594	0.2487	0.1595	0.2490	0.1619	0.2517	0.1681	0.2591
	336	0.1731	0.2645	0.1732	0.2646	0.1730	0.2643	0.1789	0.2711	0.1823	0.2744
	720	0.2033	0.2920	0.2066	0.2960	0.2214	0.3066	0.2095	0.2975	0.2145	0.3035
	Avg	0.1701	0.2600	0.1710	0.2611	0.1747	0.2637	0.1745	0.2647	0.1787	0.2696
Weather	96	0.1692	0.2185	0.1715	0.2199	0.1723	0.2223	0.1717	0.2247	0.1737	0.2277
	192	0.2102	0.2575	0.2116	0.2590	0.2116	0.2597	0.2125	0.2636	0.2128	0.2661
	336	0.2586	0.2971	0.2631	0.3072	0.2676	0.3110	0.2613	0.2997	0.2705	0.3159
	720	0.3271	0.3487	0.3303	0.3581	0.3394	0.3681	0.3354	0.3610	0.3372	0.3623
	Avg	0.2413	0.2805	0.2441	0.2860	0.2477	0.2903	0.2452	0.2872	0.2486	0.2930

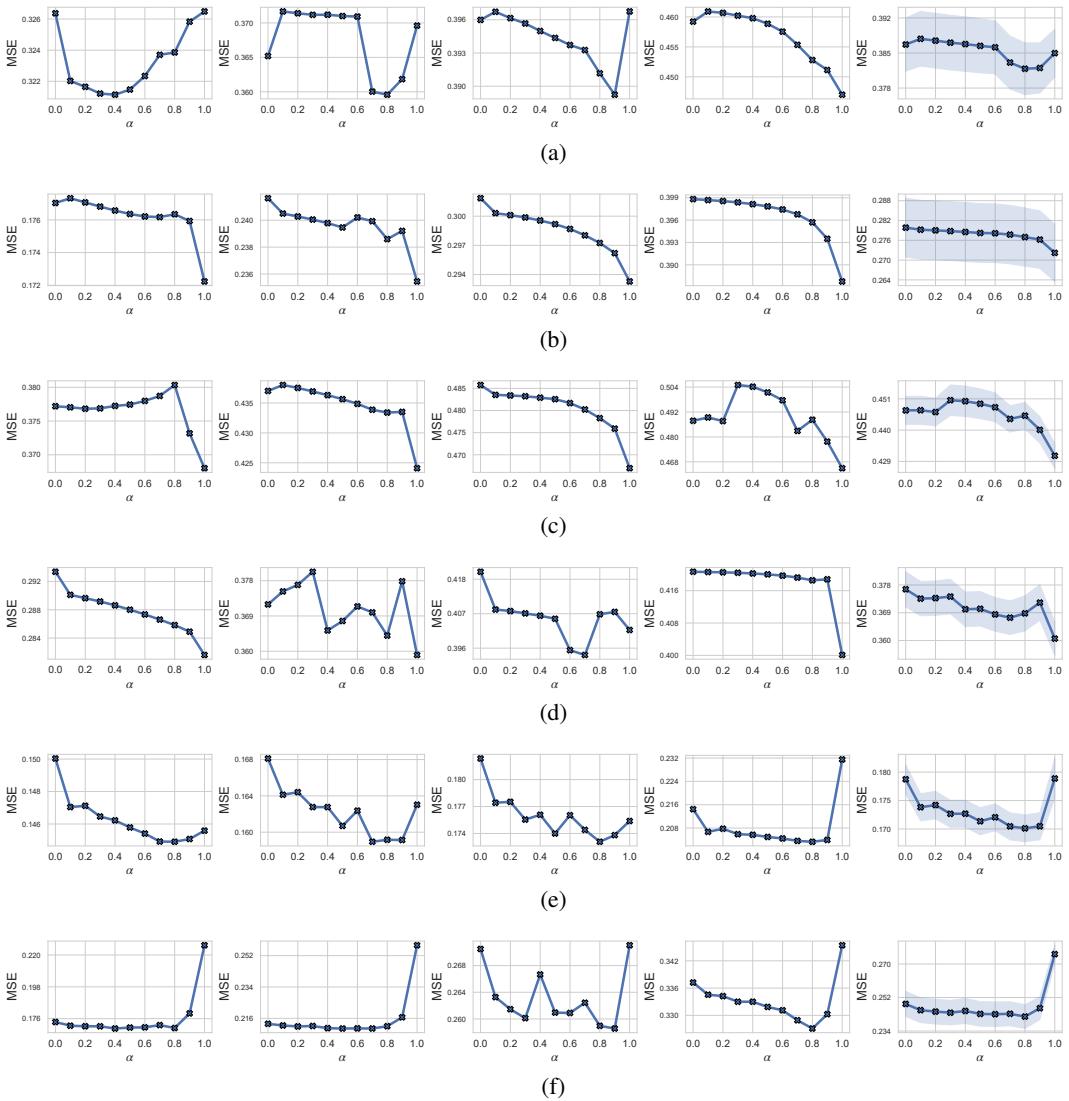


Figure 9: Time-o1 improves Fredformer performance given a wide range of transformed loss strength α . These experiments are conducted on ETTh1 (a), ETTh2 (b), ETTm1 (c), ETTm2 (d), ECL (e), Weather (f) datasets. Different columns correspond to different forecast lengths (from left to right: 96, 192, 336, 720, and their average with shaded areas being 15% confidence intervals).

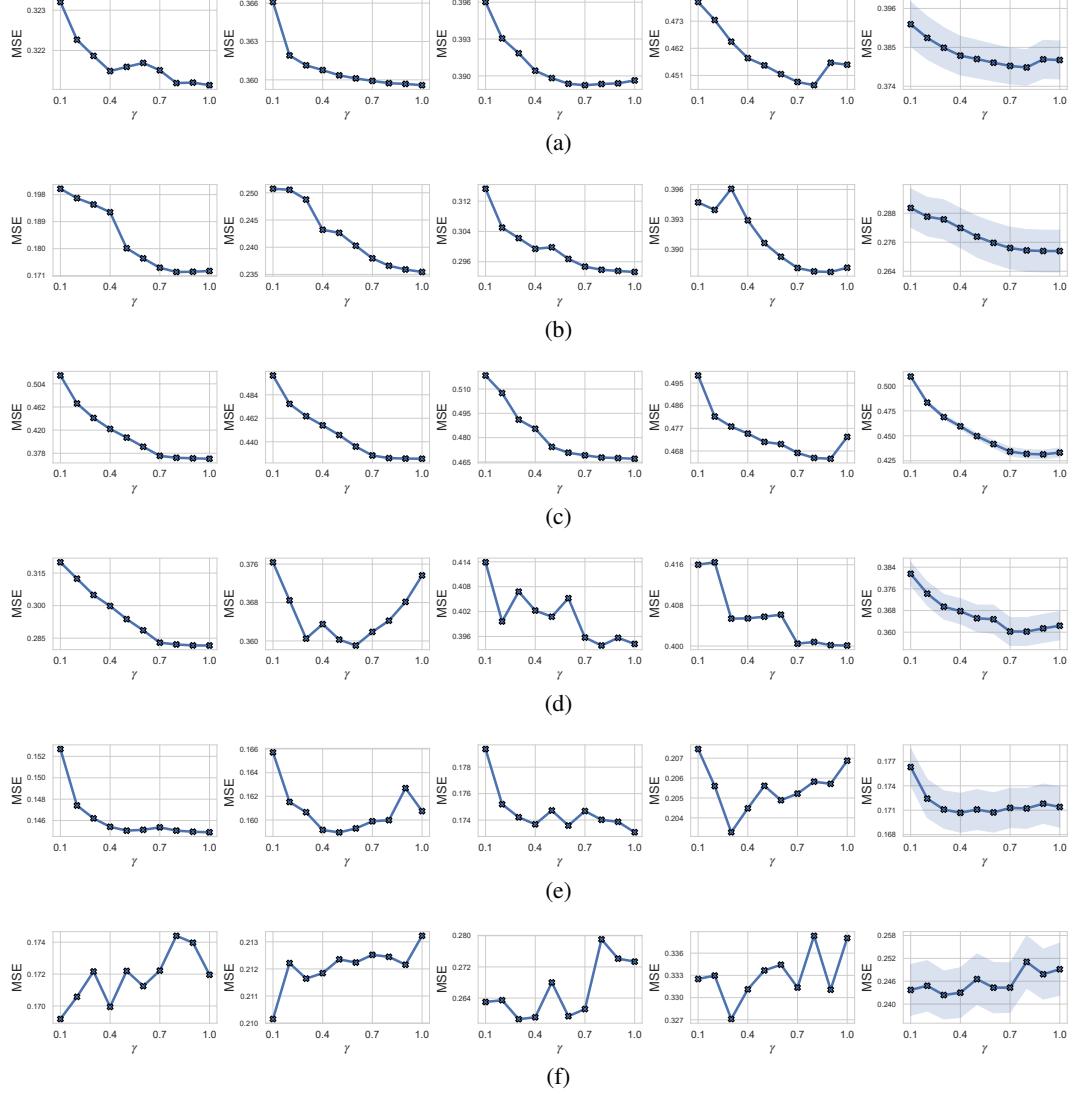


Figure 10: Time-o1 improves Fredformer performance given a wide range of rank ratio γ . These experiments are conducted on ETTh1 (a), ETTh2 (b), ETTm1 (c), ETTm2 (d), ECL (e), and Weather (f) datasets. Different columns correspond to different forecast lengths (from left to right: 96, 192, 336, 720, and their average with shaded areas being 15% confidence intervals).

Table 10: Comparable results with different loss functions.

Metrics	Loss		Time-o1		FreDF		Koopman		Dilate		Soft-DTW		DPTA		DF	
	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE
Forecast model: FredFormer																
ETTm1	96	0.321	0.357	0.326	0.355	0.335	0.368	0.337	0.367	0.332	0.363	0.332	0.364	0.326	0.361	
	192	0.360	0.378	0.363	0.380	0.366	0.384	0.364	0.384	0.370	0.386	0.370	0.386	0.365	0.382	
	336	0.389	0.400	0.392	0.400	0.399	0.408	0.397	0.406	0.406	0.409	0.409	0.410	0.396	0.404	
	720	0.447	0.435	0.455	0.440	0.456	0.441	0.457	0.443	0.478	0.450	0.476	0.448	0.459	0.444	
	Avg	0.379	0.393	0.384	0.394	0.389	0.400	0.389	0.400	0.397	0.402	0.396	0.402	0.387	0.398	
ETTh1	96	0.368	0.391	0.370	0.392	0.375	0.397	0.378	0.399	0.376	0.398	0.378	0.399	0.377	0.396	
	192	0.424	0.422	0.436	0.437	0.438	0.434	0.439	0.435	0.439	0.435	0.438	0.433	0.437	0.425	
	336	0.467	0.441	0.473	0.443	0.473	0.455	0.481	0.453	0.484	0.455	0.486	0.455	0.486	0.449	
	720	0.465	0.463	0.474	0.466	0.523	0.487	0.516	0.482	0.542	0.510	0.538	0.510	0.488	0.467	
	Avg	0.431	0.429	0.438	0.434	0.452	0.443	0.453	0.442	0.460	0.449	0.460	0.449	0.447	0.434	
ECL	96	0.151	0.245	0.152	0.247	0.166	0.263	0.158	0.253	0.168	0.266	0.158	0.253	0.161	0.258	
	192	0.166	0.256	0.166	0.257	0.174	0.267	0.170	0.263	0.218	0.313	0.216	0.307	0.174	0.269	
	336	0.181	0.274	0.183	0.278	0.188	0.280	0.190	0.286	0.197	0.291	0.199	0.295	0.194	0.290	
	720	0.213	0.304	0.216	0.304	0.232	0.318	0.229	0.316	0.240	0.322	0.235	0.322	0.235	0.319	
	Avg	0.178	0.270	0.179	0.272	0.190	0.282	0.187	0.280	0.206	0.298	0.202	0.294	0.191	0.284	
Weather	96	0.171	0.208	0.174	0.213	0.174	0.214	0.173	0.214	0.173	0.213	0.179	0.219	0.180	0.220	
	192	0.219	0.253	0.219	0.254	0.220	0.256	0.225	0.260	0.220	0.255	0.223	0.257	0.222	0.258	
	336	0.277	0.295	0.278	0.296	0.280	0.298	0.280	0.299	0.281	0.296	0.281	0.298	0.283	0.301	
	720	0.353	0.346	0.354	0.347	0.354	0.347	0.355	0.348	0.369	0.355	0.356	0.347	0.358	0.348	
	Avg	0.255	0.276	0.256	0.277	0.257	0.279	0.258	0.280	0.261	0.280	0.260	0.280	0.261	0.282	
Forecast model: iTransformer																
ETTm1	96	0.323	0.358	0.334	0.365	0.350	0.382	0.342	0.376	0.339	0.373	0.341	0.375	0.338	0.372	
	192	0.371	0.388	0.381	0.390	0.389	0.400	0.381	0.396	0.383	0.395	0.383	0.395	0.382	0.396	
	336	0.408	0.407	0.417	0.412	0.425	0.423	0.418	0.418	0.429	0.423	0.429	0.423	0.427	0.424	
	720	0.477	0.450	0.489	0.453	0.489	0.458	0.487	0.457	0.516	0.469	0.512	0.467	0.496	0.463	
	Avg	0.395	0.401	0.405	0.405	0.413	0.416	0.407	0.412	0.417	0.415	0.416	0.415	0.411	0.414	
ETTh1	96	0.378	0.393	0.378	0.395	0.392	0.411	0.385	0.405	0.387	0.405	0.386	0.405	0.385	0.405	
	192	0.428	0.423	0.428	0.423	0.446	0.442	0.440	0.437	0.443	0.439	0.441	0.439	0.440	0.437	
	336	0.473	0.450	0.470	0.447	0.483	0.461	0.480	0.457	0.494	0.464	0.489	0.462	0.480	0.457	
	720	0.473	0.469	0.490	0.484	0.501	0.491	0.504	0.492	0.557	0.520	0.538	0.509	0.504	0.492	
	Avg	0.438	0.434	0.442	0.437	0.455	0.451	0.452	0.448	0.470	0.457	0.463	0.454	0.452	0.448	
ECL	96	0.145	0.235	0.149	0.238	0.151	0.243	0.150	0.241	0.149	0.241	0.149	0.240	0.150	0.242	
	192	0.159	0.249	0.163	0.251	0.167	0.257	0.168	0.259	0.164	0.255	0.166	0.257	0.168	0.259	
	336	0.173	0.264	0.179	0.268	0.182	0.275	0.181	0.274	0.180	0.274	0.180	0.272	0.182	0.274	
	720	0.203	0.292	0.212	0.297	0.212	0.300	0.212	0.300	0.207	0.296	0.212	0.300	0.214	0.304	
	Avg	0.170	0.260	0.176	0.264	0.178	0.269	0.178	0.269	0.175	0.266	0.177	0.267	0.179	0.270	
Weather	96	0.163	0.202	0.170	0.208	0.206	0.257	0.208	0.259	0.207	0.252	0.209	0.258	0.171	0.210	
	192	0.214	0.248	0.219	0.252	0.264	0.300	0.252	0.285	0.264	0.303	0.258	0.291	0.246	0.278	
	336	0.274	0.294	0.279	0.296	0.309	0.326	0.311	0.328	0.314	0.333	0.312	0.331	0.296	0.313	
	720	0.351	0.344	0.358	0.347	0.377	0.369	0.374	0.364	0.384	0.377	0.383	0.373	0.362	0.353	
	Avg	0.251	0.272	0.257	0.276	0.289	0.313	0.286	0.309	0.292	0.316	0.291	0.313	0.269	0.289	

Table 11: Varying input sequence length results on the Weather dataset.

Models		Time-o1		iTTransformer		Time-o1		PatchTST	
Metrics		MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE
Input sequence length	96	0.163	0.202	0.171	0.210	0.175	0.213	0.200	0.244
	192	0.214	0.248	0.246	0.278	0.224	0.257	0.229	0.263
	336	0.274	0.294	0.296	0.313	0.276	0.296	0.287	0.303
	720	0.351	0.344	0.362	0.353	0.353	0.346	0.363	0.353
	Avg	0.250	0.272	0.269	0.289	0.257	0.278	0.270	0.291
	96	0.163	0.205	0.168	0.215	0.158	0.199	0.164	0.208
	192	0.210	0.248	0.213	0.253	0.204	0.242	0.225	0.269
	336	0.259	0.287	0.265	0.294	0.257	0.286	0.287	0.308
	Avg	0.241	0.270	0.247	0.277	0.238	0.266	0.254	0.283
Input sequence length	96	0.157	0.203	0.162	0.213	0.150	0.196	0.156	0.206
	192	0.199	0.246	0.211	0.256	0.196	0.241	0.222	0.277
	336	0.251	0.287	0.260	0.295	0.246	0.282	0.251	0.285
	720	0.324	0.338	0.332	0.341	0.320	0.333	0.327	0.338
	Avg	0.233	0.268	0.241	0.276	0.228	0.263	0.239	0.277
	96	0.161	0.213	0.172	0.225	0.152	0.201	0.154	0.207
	192	0.205	0.250	0.220	0.268	0.198	0.248	0.205	0.254
	336	0.254	0.292	0.282	0.311	0.248	0.284	0.248	0.288
	720	0.318	0.339	0.337	0.351	0.313	0.335	0.317	0.339
	Avg	0.235	0.274	0.253	0.289	0.228	0.267	0.231	0.272

 Table 12: Experimental results (mean \pm std) with varying seeds (2021-2025).

Dataset	ECL				Weather			
	Time-o1		DF		Time-o1		DF	
Models	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE
96	0.145 \pm 0.000	0.235 \pm 0.000	0.150 \pm 0.001	0.242 \pm 0.001	0.164 \pm 0.001	0.203 \pm 0.001	0.190 \pm 0.012	0.232 \pm 0.014
192	0.160 \pm 0.001	0.249 \pm 0.001	0.166 \pm 0.002	0.257 \pm 0.002	0.216 \pm 0.002	0.250 \pm 0.001	0.240 \pm 0.011	0.272 \pm 0.010
336	0.174 \pm 0.002	0.266 \pm 0.002	0.181 \pm 0.001	0.273 \pm 0.001	0.274 \pm 0.001	0.294 \pm 0.001	0.293 \pm 0.003	0.310 \pm 0.003
720	0.205 \pm 0.001	0.293 \pm 0.001	0.216 \pm 0.004	0.303 \pm 0.003	0.353 \pm 0.002	0.344 \pm 0.001	0.361 \pm 0.002	0.352 \pm 0.001
Avg	0.171 \pm 0.001	0.261 \pm 0.001	0.178 \pm 0.001	0.269 \pm 0.001	0.252 \pm 0.001	0.273 \pm 0.001	0.271 \pm 0.003	0.292 \pm 0.003

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