# ST–LoRA: Low–rank Adaptation for Spatio–Temporal Forecasting

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## Key Points:

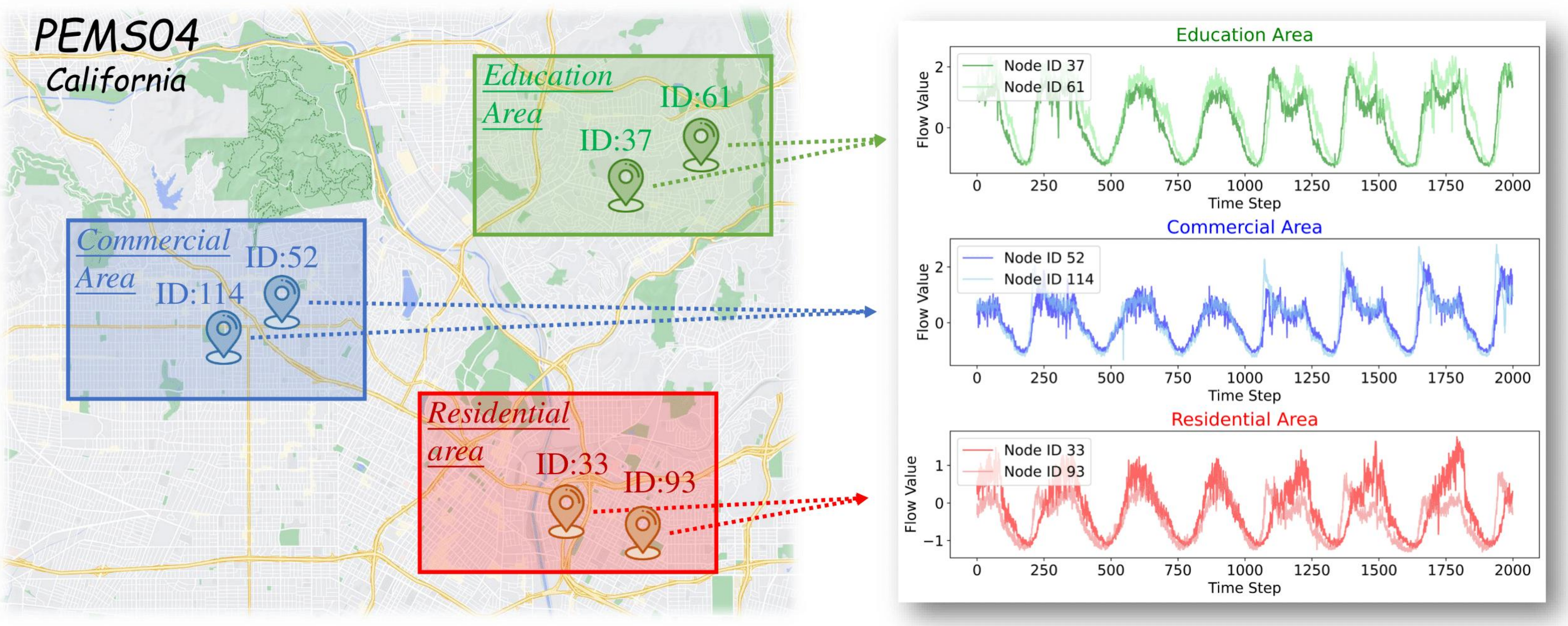
- We propose *ST-LoRA*, a plug-and-play framework with Node-Adaptive Low-rank Layers and Node-Specific Predictors for efficient modeling of node heterogeneity.
- Extensive experiments across 6 baselines and 6 real-world traffic datasets show ~7% performance improvement with <1% additional parameters.

## Background & Challenges

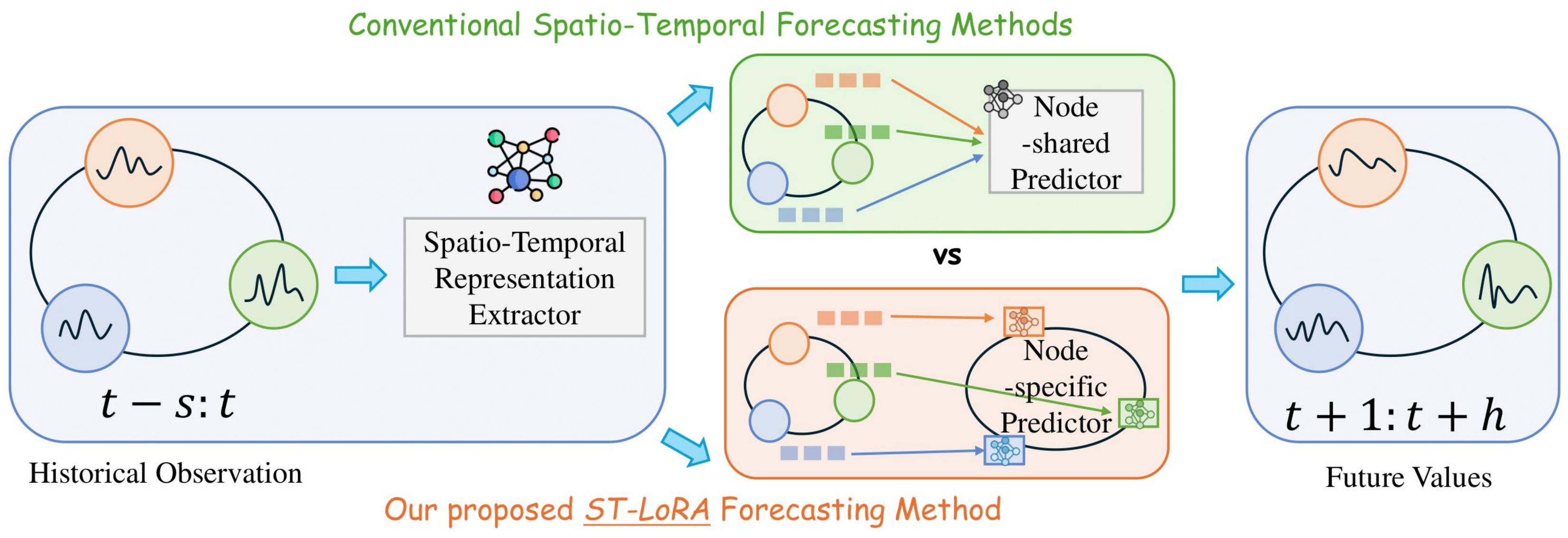
**Spatio-temporal Forecasting:**

$$[X^{(t-s+1)},\dots,X^{(t)};\mathcal{G}] \xrightarrow{\mathcal{F}(\cdot)} [X^{(t+1)},\dots,X^{(t+h)}].$$

*Facing Node heterogeneity & Over-parameterization!*




## Our Solution




***Node-shared predictor*** *struggles to address node-level heterogeneity. We need an efficient solution to the trade-off between* ***heterogeneity*** *and computational* ***complexity****.*

## Node-Adapative Low-rank Layer

$$\Delta \mathbf{W}_{v_i} = \mathbf{B}\mathbf{A}_{v_i}\cdot\frac{\alpha}{r},\quad \hat{\mathbf{y}}_i = \sigma\left(\mathbf{W}\mathbf{x} + \Delta\mathbf{W}_{v_i}\mathbf{x} + \mathbf{b}\right),$$

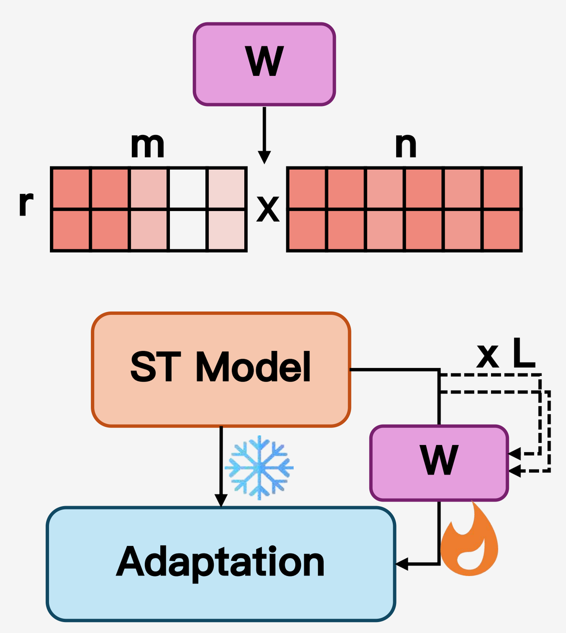
*Decompose each* ***node-level*** *parameter weights into two low-rank matrices.*

## Node-Specific Predictor

$$\mathbf{H}^{(0)} = \text{Conv2D}(\mathbf{X}_{t-T:t}),$$
$$\mathbf{H}^{(l)} = \mathbf{H}^{(l-1)} + \text{NALL}^{(l)}(\sigma(\mathbf{H}^{(l-1)})),\quad l = 1,2,\dots,L$$
$$\hat{\mathbf{Y}}_t = \mathcal{G}_t(\mathbf{H}^{(L)}),$$

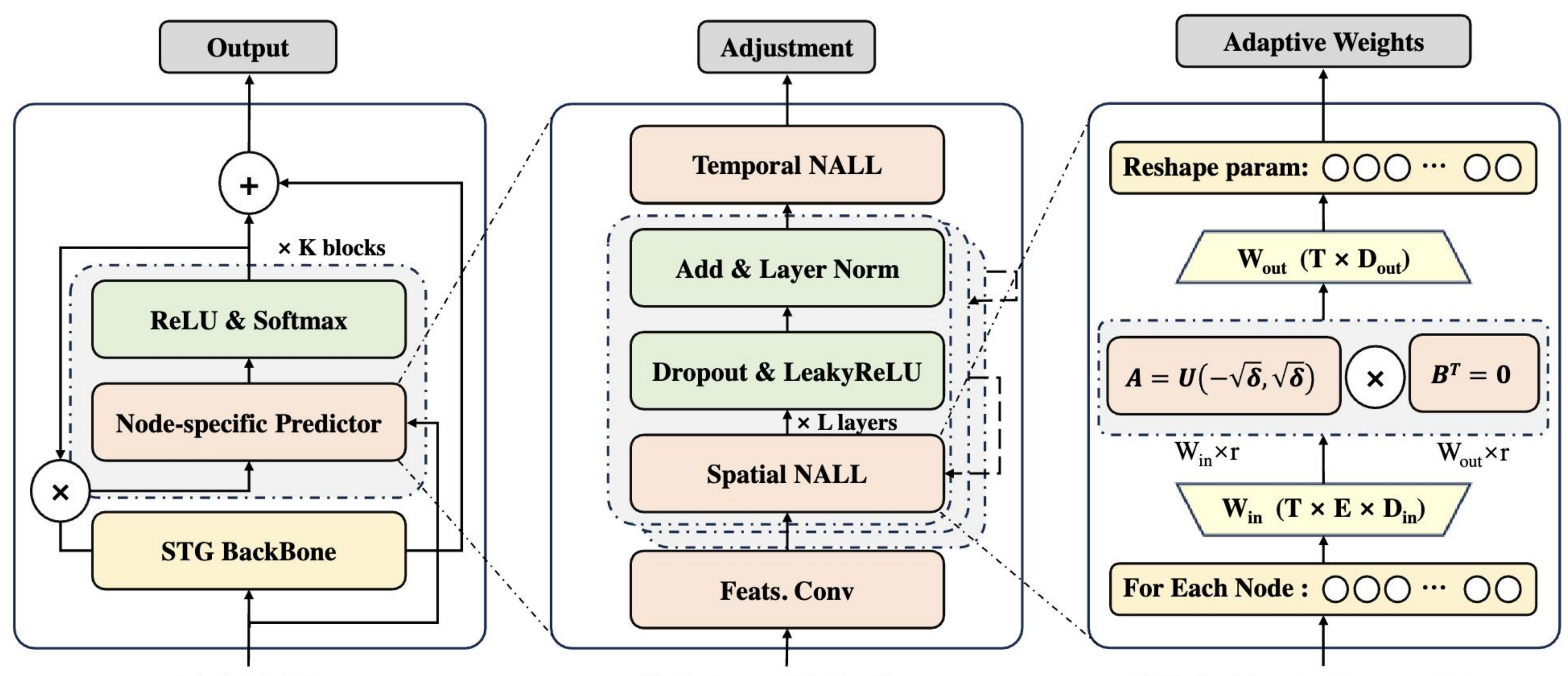
*Node specific predictor that models dynamics* ***without heavy computation****.*

## Overview




*General low-rank adaptation method for existing STGNNs!*

## ST-LoRA Framework




(a) ST-LoRA (b) Node-specific Predictor (c) Node Adaptive Low-rank Layer

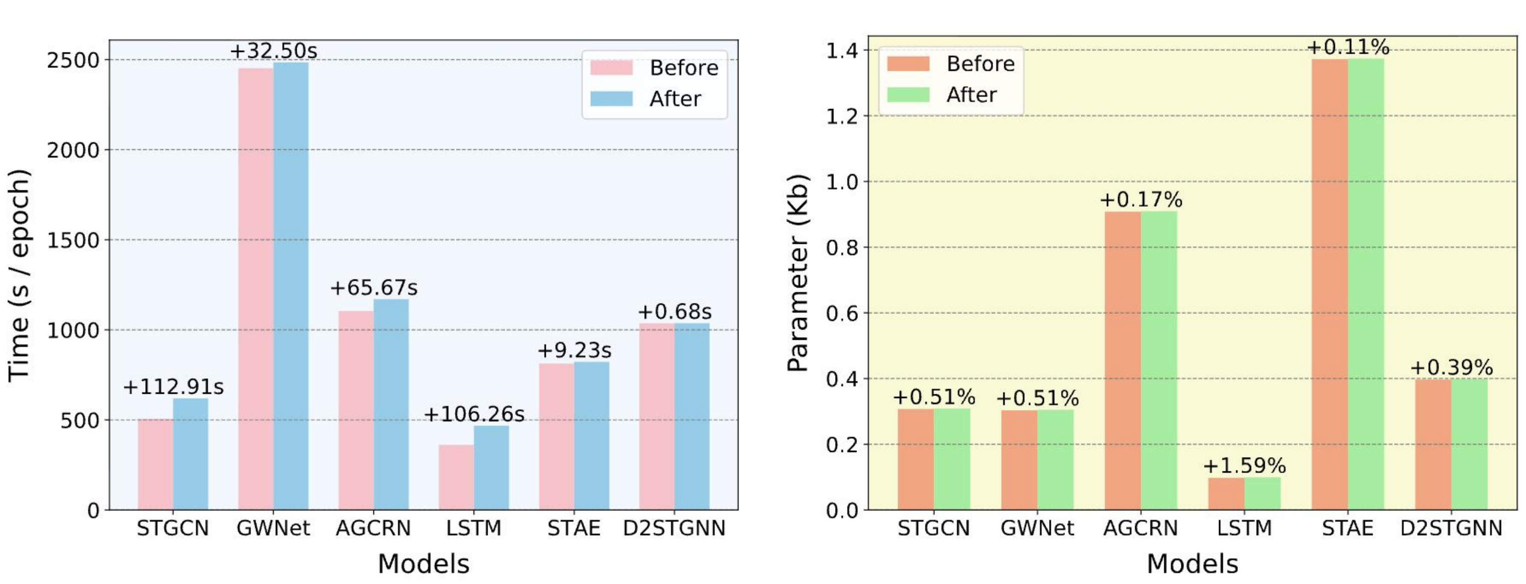
## Experiment Results

| Model | 15min MAE ↓ | 15min RMSE ↓ | 15min MAPE% ↓ | 30min MAE ↓ | 30min RMSE ↓ | 30min MAPE% ↓ | 60min MAE ↓ | 60min RMSE ↓ | 60min MAPE% ↓ | Average MAE ↓ | Average RMSE ↓ | Average MAPE% ↓ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HA | $28.92_{\pm1.25}$ | $42.69_{\pm1.82}$ | $20.31_{\pm0.89}$ | $33.73_{\pm1.28}$ | $49.37_{\pm1.85}$ | $24.01_{\pm0.91}$ | $46.97_{\pm1.31}$ | $67.43_{\pm1.89}$ | $35.11_{\pm0.92}$ | $38.03_{\pm1.28}$ | $59.24_{\pm1.85}$ | $27.88_{\pm0.91}$ |
| VAR | $21.94_{\pm0.62}$ | $34.30_{\pm1.02}$ | $16.42_{\pm0.48}$ | $23.72_{\pm0.71}$ | $36.58_{\pm1.08}$ | $18.02_{\pm0.52}$ | $26.76_{\pm0.82}$ | $40.28_{\pm1.23}$ | $20.94_{\pm0.64}$ | $23.51_{\pm0.72}$ | $36.39_{\pm1.11}$ | $17.85_{\pm0.55}$ |
| SVR | $22.52_{\pm0.68}$ | $35.30_{\pm1.12}$ | $14.71_{\pm0.45}$ | $27.63_{\pm0.78}$ | $42.23_{\pm1.25}$ | $18.29_{\pm0.49}$ | $37.86_{\pm1.15}$ | $56.01_{\pm1.70}$ | $26.72_{\pm0.82}$ | $28.66_{\pm0.87}$ | $44.59_{\pm1.36}$ | $19.15_{\pm0.59}$ |
| LSTM | $21.94_{\pm0.59}$ | $33.37_{\pm0.93}$ | $15.32_{\pm0.40}$ | $25.83_{\pm0.66}$ | $39.10_{\pm1.04}$ | $20.35_{\pm0.43}$ | $36.41_{\pm0.82}$ | $50.73_{\pm1.28}$ | $29.92_{\pm0.56}$ | $27.14_{\pm0.69}$ | $41.59_{\pm1.08}$ | $18.20_{\pm0.46}$ |
| LSTM+ | $18.89_{\pm0.58}$ | $29.96_{\pm0.91}$ | $13.02_{\pm0.40}$ | $21.31_{\pm0.65}$ | $34.22_{\pm1.04}$ | $13.96_{\pm0.43}$ | $26.34_{\pm0.80}$ | $41.30_{\pm1.26}$ | $18.26_{\pm0.56}$ | $22.18_{\pm0.68}$ | $35.16_{\pm1.07}$ | $15.08_{\pm0.46}$ |
| $\Delta$ | $-3.05_{\pm0.18}$ | $-3.41_{\pm0.20}$ | $-2.30_{\pm0.14}$ | $-4.52_{\pm0.27}$ | $-4.88_{\pm0.29}$ | $-6.39_{\pm0.38}$ | $-10.07_{\pm0.60}$ | $-9.43_{\pm0.57}$ | $-11.66_{\pm0.70}$ | $-4.96_{\pm0.30}$ | $-6.43_{\pm0.39}$ | $-3.12_{\pm0.19}$ |
| STGCN | $19.45_{\pm0.59}$ | $30.12_{\pm0.92}$ | $14.21_{\pm0.43}$ | $21.85_{\pm0.62}$ | $34.43_{\pm0.97}$ | $14.13_{\pm0.44}$ | $26.97_{\pm0.68}$ | $41.11_{\pm1.06}$ | $16.84_{\pm0.48}$ | $22.70_{\pm0.63}$ | $35.55_{\pm0.98}$ | $14.59_{\pm0.45}$ |
| STGCN+ | $19.12_{\pm0.58}$ | $29.72_{\pm0.91}$ | $13.89_{\pm0.42}$ | $19.92_{\pm0.61}$ | $31.63_{\pm0.96}$ | $13.77_{\pm0.42}$ | $22.07_{\pm0.67}$ | $34.47_{\pm1.05}$ | $15.42_{\pm0.47}$ | $20.37_{\pm0.62}$ | $31.94_{\pm0.97}$ | $14.36_{\pm0.44}$ |
| $\Delta$ | $-0.33_{\pm0.02}$ | $-0.40_{\pm0.02}$ | $-0.32_{\pm0.02}$ | $-1.93_{\pm0.12}$ | $-2.80_{\pm0.17}$ | $-0.36_{\pm0.02}$ | $-4.90_{\pm0.29}$ | $-6.64_{\pm0.40}$ | $-1.42_{\pm0.09}$ | $-2.33_{\pm0.14}$ | $-3.61_{\pm0.22}$ | $-0.23_{\pm0.01}$ |
| GWNet | $18.65_{\pm0.57}$ | $29.24_{\pm0.89}$ | $13.82_{\pm0.42}$ | $19.57_{\pm0.60}$ | $30.62_{\pm0.92}$ | $13.28_{\pm0.39}$ | $23.07_{\pm0.70}$ | $35.35_{\pm1.08}$ | $17.34_{\pm0.53}$ | $25.45_{\pm0.62}$ | $39.70_{\pm0.97}$ | $17.29_{\pm0.45}$ |
| GWNet+ | $17.89_{\pm0.55}$ | $28.52_{\pm0.87}$ | $12.64_{\pm0.39}$ | $18.88_{\pm0.58}$ | $29.38_{\pm0.89}$ | $13.06_{\pm0.40}$ | $20.89_{\pm0.64}$ | $32.96_{\pm1.00}$ | $14.92_{\pm0.46}$ | $19.22_{\pm0.59}$ | $30.62_{\pm0.93}$ | $13.54_{\pm0.41}$ |
| $\Delta$ | $-0.76_{\pm0.05}$ | $-0.72_{\pm0.04}$ | $-1.18_{\pm0.07}$ | $-0.69_{\pm0.04}$ | $-1.24_{\pm0.07}$ | $-0.22_{\pm0.01}$ | $-2.18_{\pm0.13}$ | $-2.39_{\pm0.14}$ | $-2.42_{\pm0.15}$ | $-6.23_{\pm0.37}$ | $-9.08_{\pm0.54}$ | $-3.75_{\pm0.23}$ |
| AGCRN | $18.12_{\pm0.55}$ | $29.45_{\pm0.90}$ | $12.85_{\pm0.39}$ | $18.77_{\pm0.57}$ | $30.08_{\pm0.92}$ | $12.97_{\pm0.40}$ | $20.41_{\pm0.62}$ | $32.87_{\pm1.00}$ | $14.38_{\pm0.44}$ | $19.83_{\pm0.58}$ | $32.26_{\pm0.94}$ | $13.40_{\pm0.41}$ |
| AGCRN+ | $17.83_{\pm0.54}$ | $29.16_{\pm0.89}$ | $12.55_{\pm0.38}$ | $18.63_{\pm0.57}$ | $29.99_{\pm0.91}$ | $12.82_{\pm0.39}$ | $19.97_{\pm0.61}$ | $32.37_{\pm0.99}$ | $13.78_{\pm0.42}$ | $18.81_{\pm0.57}$ | $30.51_{\pm0.93}$ | $13.05_{\pm0.40}$ |
| $\Delta$ | $-0.29_{\pm0.02}$ | $-0.29_{\pm0.02}$ | $-0.30_{\pm0.02}$ | $-0.14_{\pm0.01}$ | $-0.09_{\pm0.01}$ | $-0.15_{\pm0.01}$ | $-0.44_{\pm0.03}$ | $-0.50_{\pm0.03}$ | $-0.60_{\pm0.04}$ | $-1.02_{\pm0.06}$ | $-1.75_{\pm0.11}$ | $-0.35_{\pm0.02}$ |
| STAE | $17.95_{\pm0.55}$ | $29.12_{\pm0.89}$ | $12.65_{\pm0.39}$ | $18.92_{\pm0.58}$ | $30.09_{\pm0.92}$ | $13.35_{\pm0.41}$ | $21.06_{\pm0.64}$ | $33.37_{\pm1.02}$ | $15.55_{\pm0.47}$ | $19.31_{\pm0.59}$ | $30.86_{\pm0.94}$ | $13.85_{\pm0.42}$ |
| STAE+ | $17.65_{\pm0.54}$ | $28.73_{\pm0.88}$ | $12.45_{\pm0.38}$ | $18.62_{\pm0.57}$ | $29.55_{\pm0.90}$ | $13.29_{\pm0.41}$ | $20.40_{\pm0.62}$ | $32.38_{\pm0.99}$ | $15.00_{\pm0.46}$ | $18.89_{\pm0.58}$ | $30.22_{\pm0.92}$ | $13.58_{\pm0.41}$ |
| $\Delta$ | $-0.30_{\pm0.02}$ | $-0.39_{\pm0.02}$ | $-0.20_{\pm0.01}$ | $-0.30_{\pm0.02}$ | $-0.54_{\pm0.03}$ | $-0.06_{\pm0.01}$ | $-0.66_{\pm0.04}$ | $-0.99_{\pm0.06}$ | $-0.55_{\pm0.03}$ | $-0.42_{\pm0.03}$ | $-0.64_{\pm0.04}$ | $-0.27_{\pm0.02}$ |
| D2STGNN | $18.95_{\pm0.58}$ | $29.85_{\pm0.91}$ | $14.82_{\pm0.45}$ | $19.96_{\pm0.61}$ | $31.34_{\pm0.95}$ | $15.52_{\pm0.47}$ | $23.34_{\pm0.71}$ | $35.89_{\pm1.09}$ | $17.39_{\pm0.53}$ | $20.75_{\pm0.63}$ | $32.36_{\pm0.99}$ | $15.91_{\pm0.49}$ |
| D2STGNN+ | $18.25_{\pm0.56}$ | $28.92_{\pm0.88}$ | $14.12_{\pm0.43}$ | $19.21_{\pm0.59}$ | $30.50_{\pm0.93}$ | $13.46_{\pm0.41}$ | $21.73_{\pm0.66}$ | $33.73_{\pm1.03}$ | $17.00_{\pm0.52}$ | $19.73_{\pm0.60}$ | $31.05_{\pm0.95}$ | $14.86_{\pm0.45}$ |
| $\Delta$ | $-0.70_{\pm0.04}$ | $-0.93_{\pm0.06}$ | $-0.70_{\pm0.04}$ | $-0.75_{\pm0.05}$ | $-0.84_{\pm0.05}$ | $-2.06_{\pm0.12}$ | $-1.61_{\pm0.10}$ | $-2.16_{\pm0.13}$ | $-0.39_{\pm0.02}$ | $-1.02_{\pm0.06}$ | $-1.31_{\pm0.08}$ | $-1.05_{\pm0.06}$ |

| Dataset | 15min MAE | 15min RMSE | 15min MAPE% | 30min MAE | 30min RMSE | 30min MAPE% | 60min MAE | 60min RMSE | 60min MAPE% | Average MAE | Average RMSE | Average MAPE% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PEMS04 | $-0.33_{\pm0.02}$ | $-0.40_{\pm0.03}$ | $-0.07_{\pm0.01}$ | $-1.45_{\pm0.09}$ | $-2.50_{\pm0.15}$ | $-0.10_{\pm0.01}$ | $-4.94_{\pm0.30}$ | $-6.61_{\pm0.40}$ | $-1.28_{\pm0.08}$ | $-2.24_{\pm0.14}$ | $-3.17_{\pm0.19}$ | $-0.48_{\pm0.03}$ |
| PEMS08 | $-0.20_{\pm0.01}$ | $-1.09_{\pm0.07}$ | $-0.57_{\pm0.03}$ | $-1.37_{\pm0.08}$ | $-1.79_{\pm0.11}$ | $-0.30_{\pm0.02}$ | $-7.63_{\pm0.46}$ | $-5.86_{\pm0.35}$ | $-1.28_{\pm0.08}$ | $-3.07_{\pm0.18}$ | $-2.91_{\pm0.17}$ | $-0.72_{\pm0.04}$ |
| PEMS03 | $-0.31_{\pm0.02}$ | $-0.51_{\pm0.03}$ | $-0.72_{\pm0.04}$ | $-0.22_{\pm0.01}$ | $-0.23_{\pm0.01}$ | $-0.60_{\pm0.04}$ | $-0.45_{\pm0.03}$ | $-0.35_{\pm0.02}$ | $-1.25_{\pm0.08}$ | $-0.33_{\pm0.02}$ | $-0.36_{\pm0.02}$ | $-0.86_{\pm0.05}$ |
| PEMS07 | $-0.26_{\pm0.02}$ | $-0.29_{\pm0.02}$ | $-0.16_{\pm0.01}$ | $-0.38_{\pm0.02}$ | $-0.35_{\pm0.02}$ | $-0.31_{\pm0.02}$ | $-0.59_{\pm0.04}$ | $-0.59_{\pm0.04}$ | $-0.32_{\pm0.02}$ | $-0.41_{\pm0.03}$ | $-0.41_{\pm0.03}$ | $-0.26_{\pm0.02}$ |
| METR-LA | $-0.10_{\pm0.01}$ | $-0.36_{\pm0.02}$ | $-0.03_{\pm0.00}$ | $-0.33_{\pm0.02}$ | $-0.83_{\pm0.05}$ | $-0.80_{\pm0.05}$ | $-1.05_{\pm0.06}$ | $-1.97_{\pm0.12}$ | $-2.30_{\pm0.14}$ | $-0.49_{\pm0.03}$ | $-1.05_{\pm0.06}$ | $-1.04_{\pm0.06}$ |
| PEMSBAY | $-0.04_{\pm0.00}$ | $-0.06_{\pm0.00}$ | $-0.11_{\pm0.01}$ | $-0.10_{\pm0.01}$ | $-0.45_{\pm0.03}$ | $-0.23_{\pm0.01}$ | $-0.50_{\pm0.03}$ | $-1.14_{\pm0.07}$ | $-1.02_{\pm0.06}$ | $-0.21_{\pm0.01}$ | $-0.55_{\pm0.03}$ | $-0.45_{\pm0.03}$ |

**Extensive Experiments across Multiple Models and Datasets.**

## Comprehensive Efficiency Study




(a) Processing time. (b) Training parameter.

## Conclusion

Our paper highlights the potential of **low-rank adaptation** techniques to improve spatio-temporal forecasting in real-world scenarios, achieving consistent enhanced performance across multiple datasets and models.

## Future Work

Develop a **unified, scalable framework** for flexible LoRA variants, and benchmark across diverse spatio-temporal models and datasets.