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Context-aware train delay propagations: a graph attention network approach

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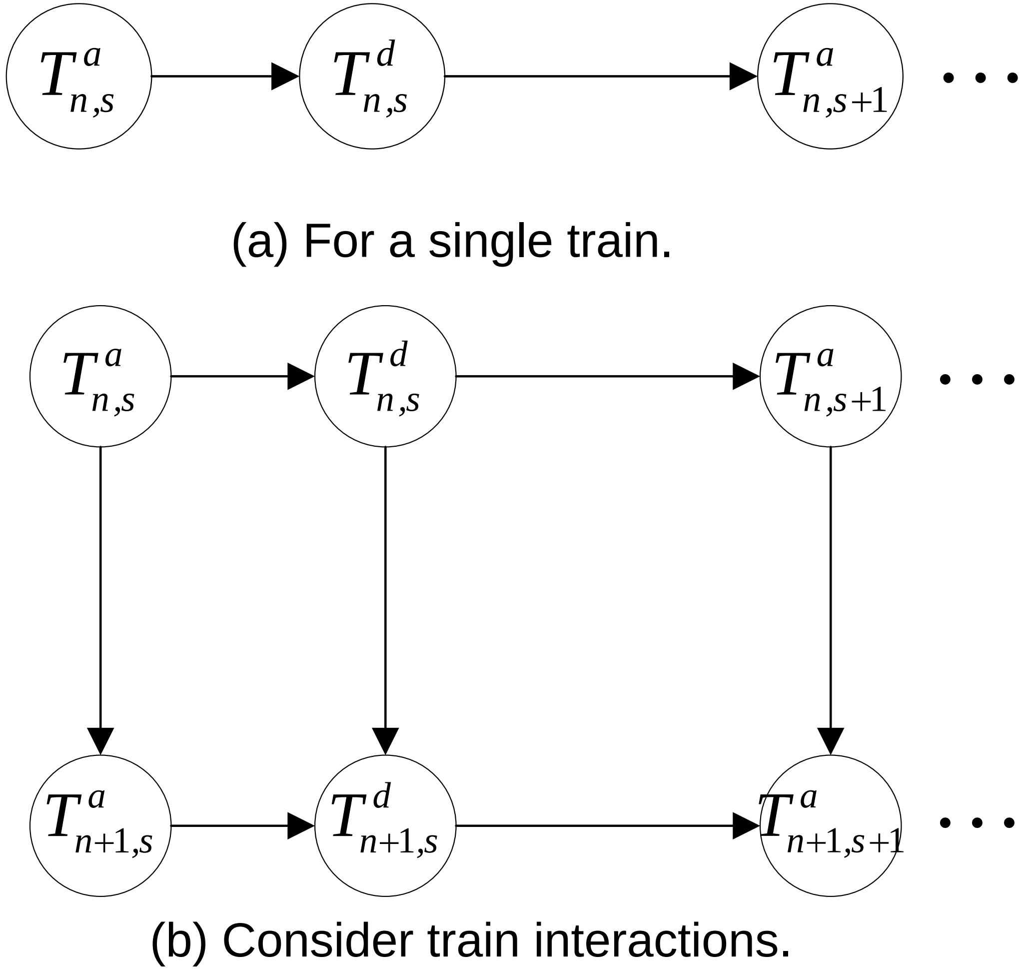
Background and problem: background

(1) Trains are inevitably delayed due to factors inside or outside the systems;

(2) The train delays show the following characteristics:

- ✓ **Uncertainty**: interruptions and the pre-scheduled recovery times and buffer times utilization are uncertain.
- ✓ **Dynamics**: train delays are typically temporal/time-series data, showing auto-correlation, cross-correlation, and trends; These correlations and trends usually differ from time and space.
- ✓ **Interactions**: train operations are influenced by the train running process, dwelling process, and train headways; These influencing factors have different impacts on the delay propagations (i.e., their importance to delay propagation is different).

Background and problem: problem



Traditional delay propagation model.

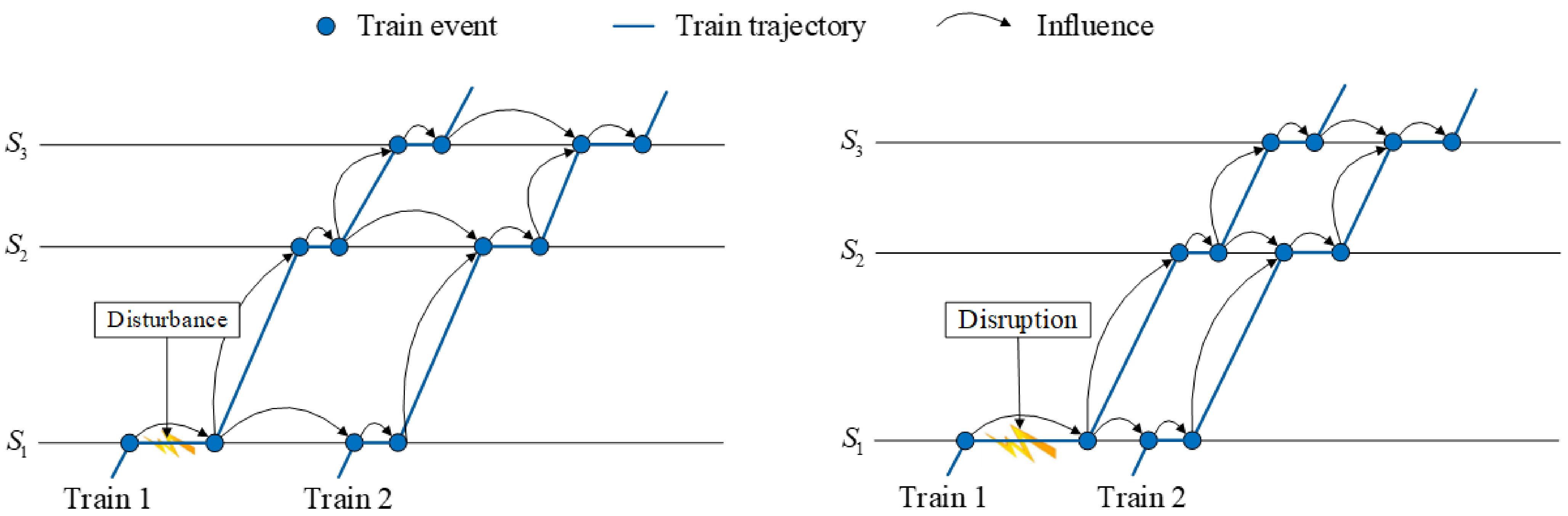
- ✓ **The traditional delay propagation models (e.g., timed event graph, Bayesian networks):** the nodes represent the train arrival and departure events, and the connections/arcs describe the relationships of nodes.

- ✓ **Problem:** these models cannot address diverse interactions (e.g., the strength of influences between factors).

Background and problem: problem

Train operation characteristics:

- ✓ Tunning times, dwelling times are different over time, space, and trains services.
- ✓ Train headways are diverse over time and space and under different situations.



Train operations

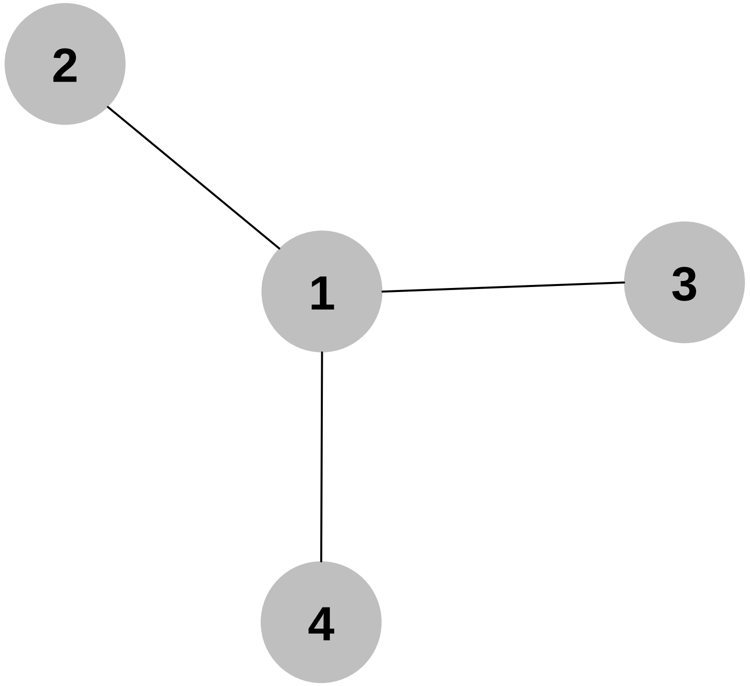
Method: GAT (graph attention networks)

A graph (G): G = (V, E, U).

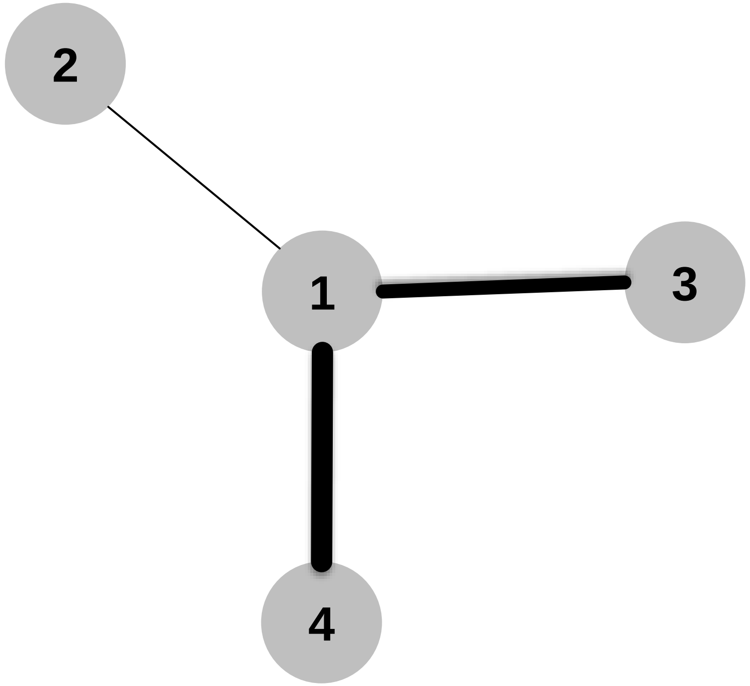
V: Vertex (or node) attributes, e.g., node identity, number of neighbors

E: Edge (or link) attributes and directions, e.g., edge identity, edge weight

U: Global (or master node) attributes, e.g., number of nodes, longest path

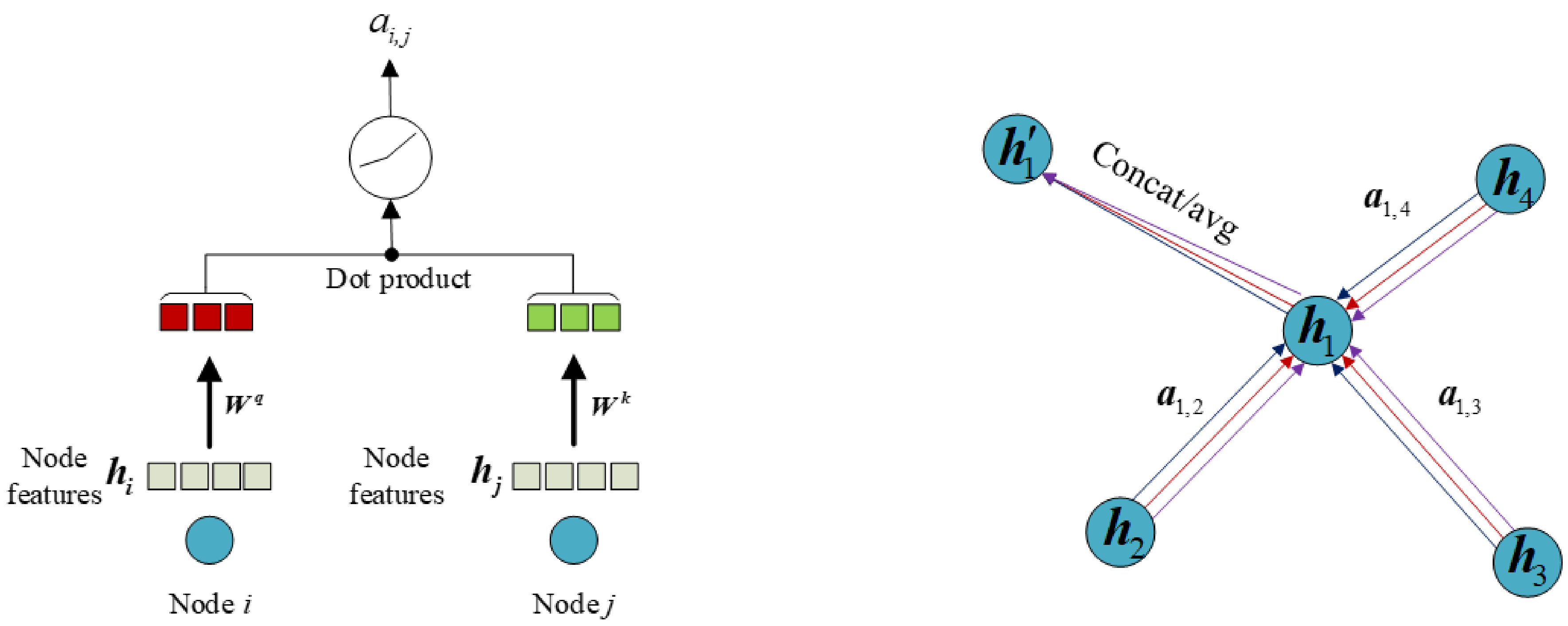


The GNN (graph neural network) model.



The GAT model.

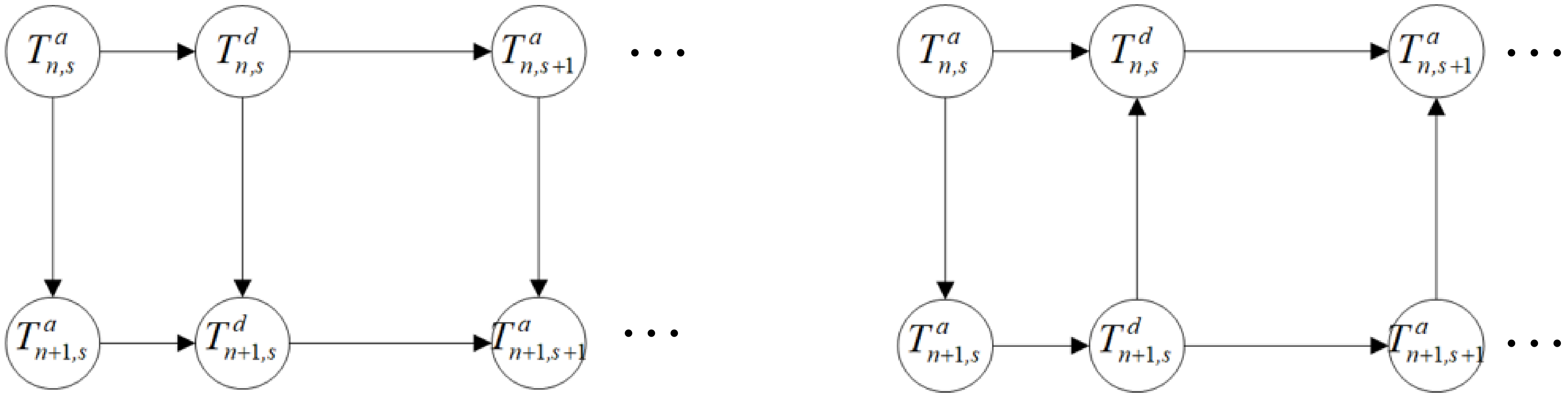
Method: GAT (the self-attention)



The attention mechanism: (left) calculation of attention score, and (right) multi-head attention.

Method: Graph structure for delay propagation

To consider the interactions between trains:



Graph structure for delay prediction from Corman and Kecman. (2018): (left) without overtaking, and (right) with an overtaking in station *s*.

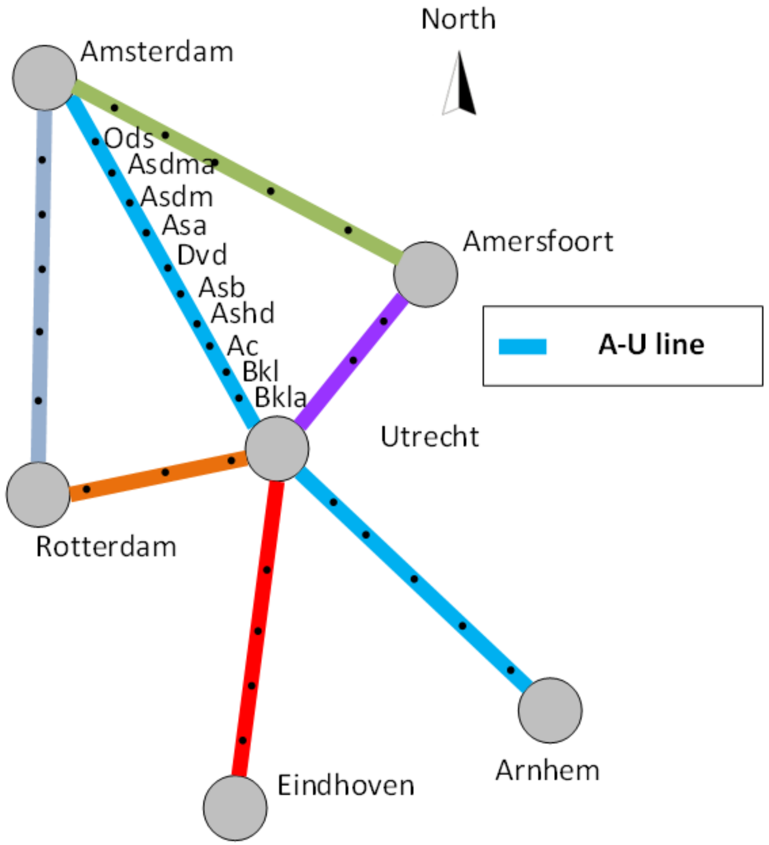
Corman and Kecman, 2018. Stochastic prediction of train delays in real-time using Bayesian networks. Transportation Research Part C: Emerging Technologies 95, 599-615.

Case study: data description

Dataset: Amsterdam to Utrecht (A-U) main railway line in the Dutch railway network.

- ✓ September, 2017 to December, 2017 (only weekdays).
- ✓ 7 stations, 6 sections, approximately 45 km;
- ✓ 9,600 train services per station in a single direction.

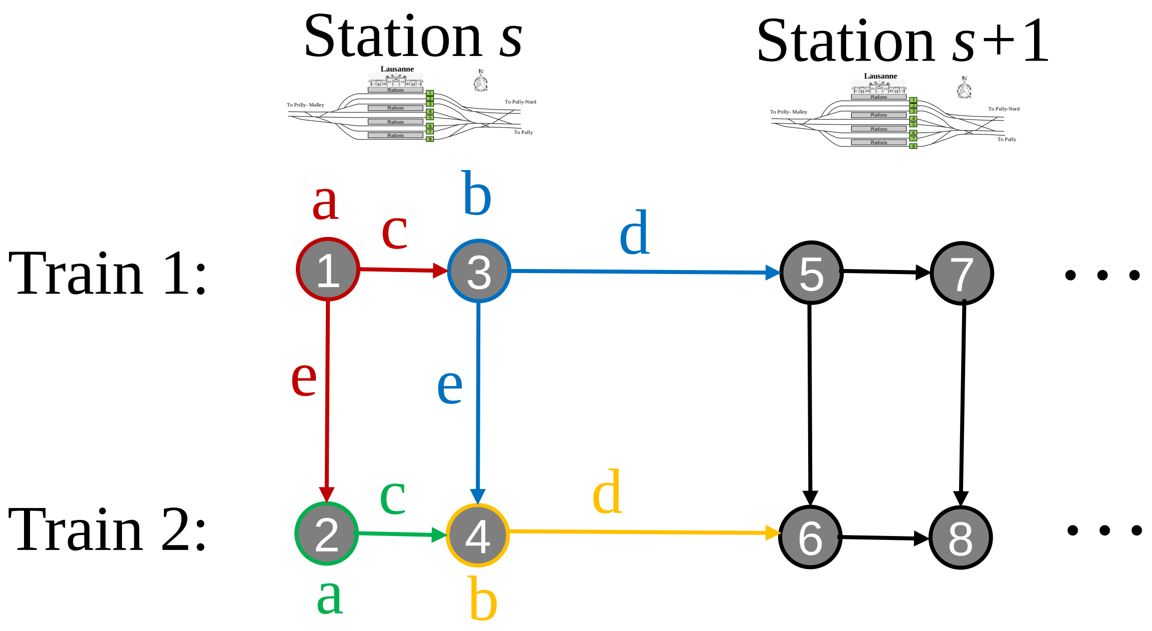
The dataset includes planned and actual arrival/departure times for each train at each station (in minute).



Case study: experiment setting

Influence parameters of delay propagation:

a. Arrival delays at each station.
b. Departure delays at each station.
c. Planned and actual dwelling times at stations.
d. Planned and actual running times in sections.
e. Planned and actual headways between trains.



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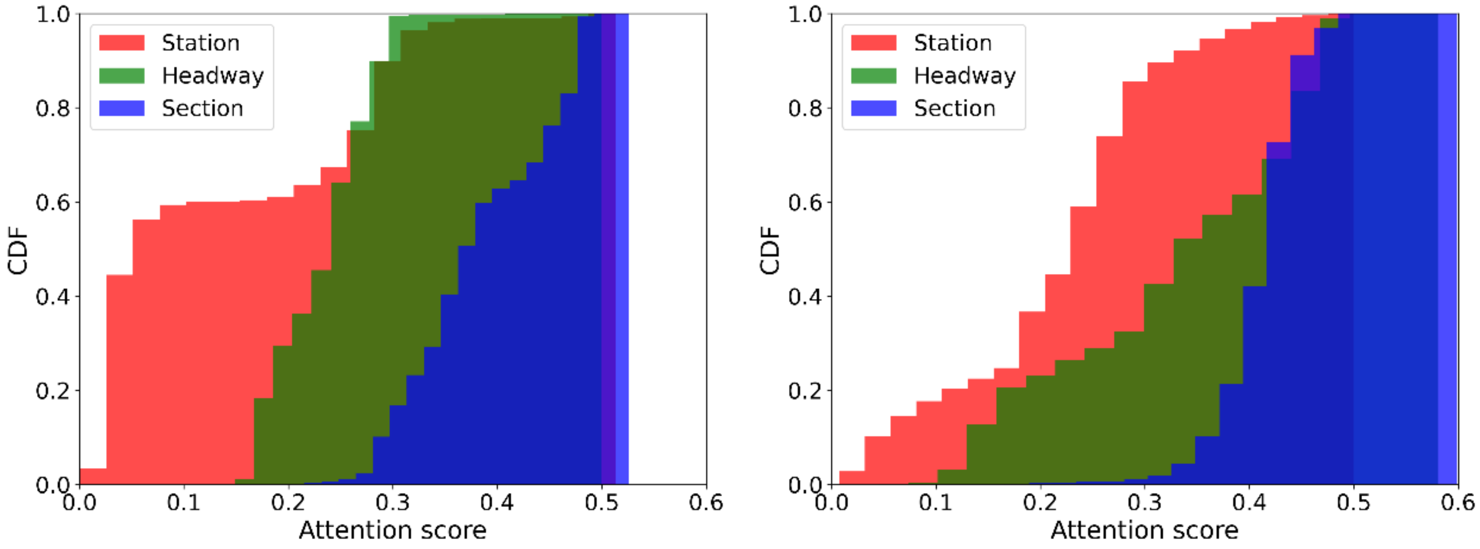
Case study: results



The attention scores of train running times (section) and dwelling times (station) processes and headways.

Explanations:

- ✓ Supplement/recovery times and buffer times are always pre-scheduled in sections and between trains;

- ✓ Train dwelling process is relatively short (e.g., over 90% of trains' dwelling times at stations are less than 1 minute), with limited supplement/recovery times to influence the delay propagation.

Case study: results

Hypothesis test:

- ✓ **Objective:** to test if two groups of observations follow the same distribution.
- ✓ **Method:** Kolmogorov-Smirnov (K-S) test (Stephens, 1974).
- ✓ **The null hypothesis:** the two sets of observations follow the same distribution, at a significance level of 5%

K-S testing results.

Connections	Layer 1		Layer 2	
	Statistic (D)	p-value	Statistic (D)	p-value
Running times and dewlling times	0.768	< 2.2e-16	0.878	< 2.2e-16
Running times and headways	0.866	< 2.2e-16	0.468	< 2.2e-16
Dwelling times and headways	0.600	<2.20e-16	0.526	< 2.2e-16

Stephens, M.A., 1974. EDF statistics for goodness of fit and some comparisons. Journal of the American statistical Association 69(347), 730-737.

Case study: predictive results

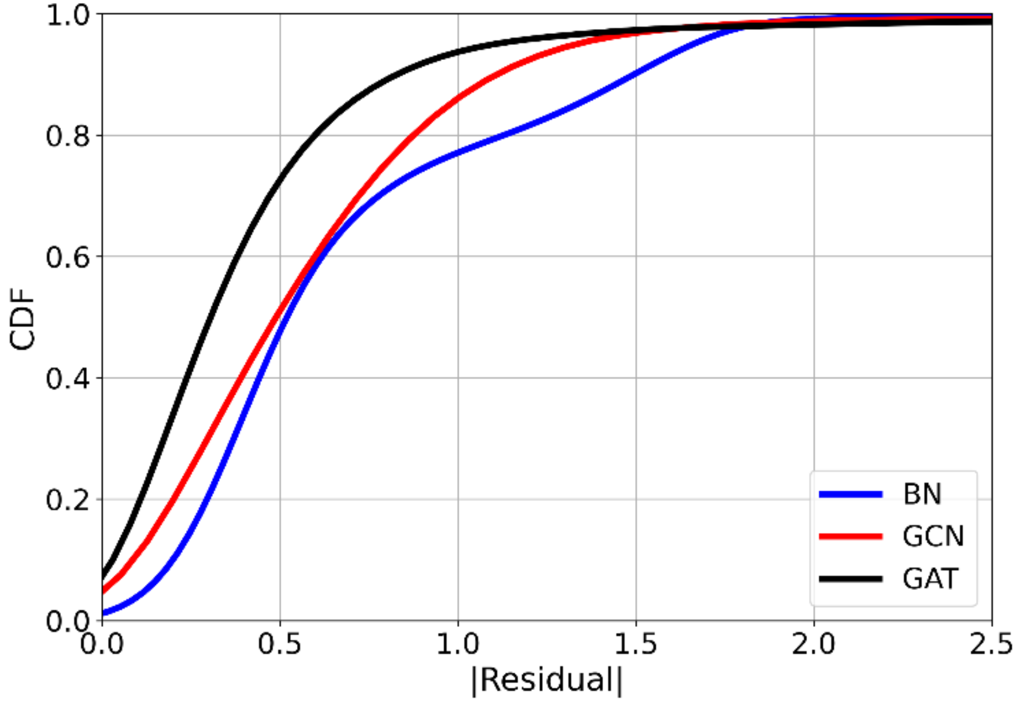
Benchmark:

✓ Bayesian networks (BN).

✓ Graph convolutional networks (GCN).

Predictive errors of the models.

Model	MAE	RMSE
BN	0.684	0.848
GCN	0.583	0.861
GAT	0.413	0.654



Cumulative distribution function (CDF) of residuals.

Conclusion and future directions

Conclusions/contributions:

- ✓ The model is built on the graph, retaining the advantages (easy understanding and high interpretability) of the graph- and network-based models for train delay propagation problems.
- ✓ The GAT model uses an attention mechanism to uncover the importance of factors to delay propagation and assigns weights to different connections/factors, allowing the model pay more attention on the important factors.

Future directions:

- ✓ To investigate the attention scores under different situations, e.g., over time, space, delay lengths, and headways.
- ✓ To find critical factors for train operations delays and delay propagation.

THANKS

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