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Application of Physics-informed Deep Learning for Traffic State Estimation

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Motivation

Transport authorities require faster, more robust and data-efficient traffic state estimation (TSE) methods in detector-free regions on highway merges. As floating car data (FCD) become increasingly popular, concept of data fusion gains the attention of researchers for filling the missing information between fixed-detectors. This thesis proposed a physics-informed deep learning (PIDL) approach that integrates an additional delayed model in the base Greenshields-LWR PINN architecture which is incapable of modeling traffic instabilities. The extended PIDL model trained with data collected from both stationary and FCD is designed to capture and reconstruct heterogeneous traffic such as stop-and-go (S&G) waves easier.

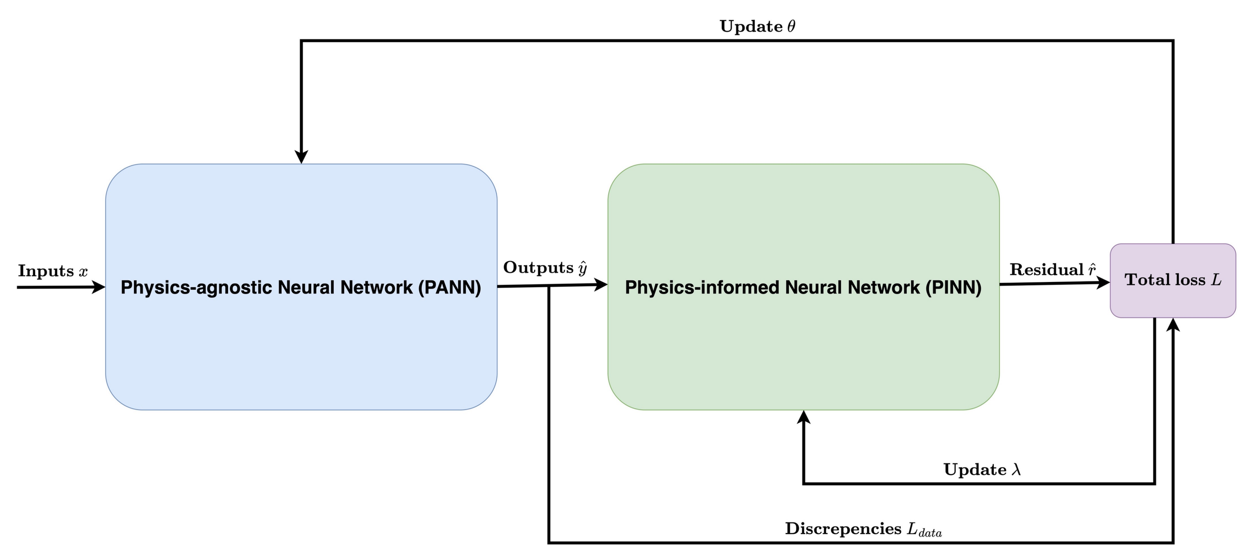
Methodology

The Powell Street on-ramp section of I80 highway in the NGSIM dataset is used in this thesis to test the robustness of PIDL models. Speed collected by FCD and density collected by stationary loop detectors are used to train the deep learning models simultaneously.

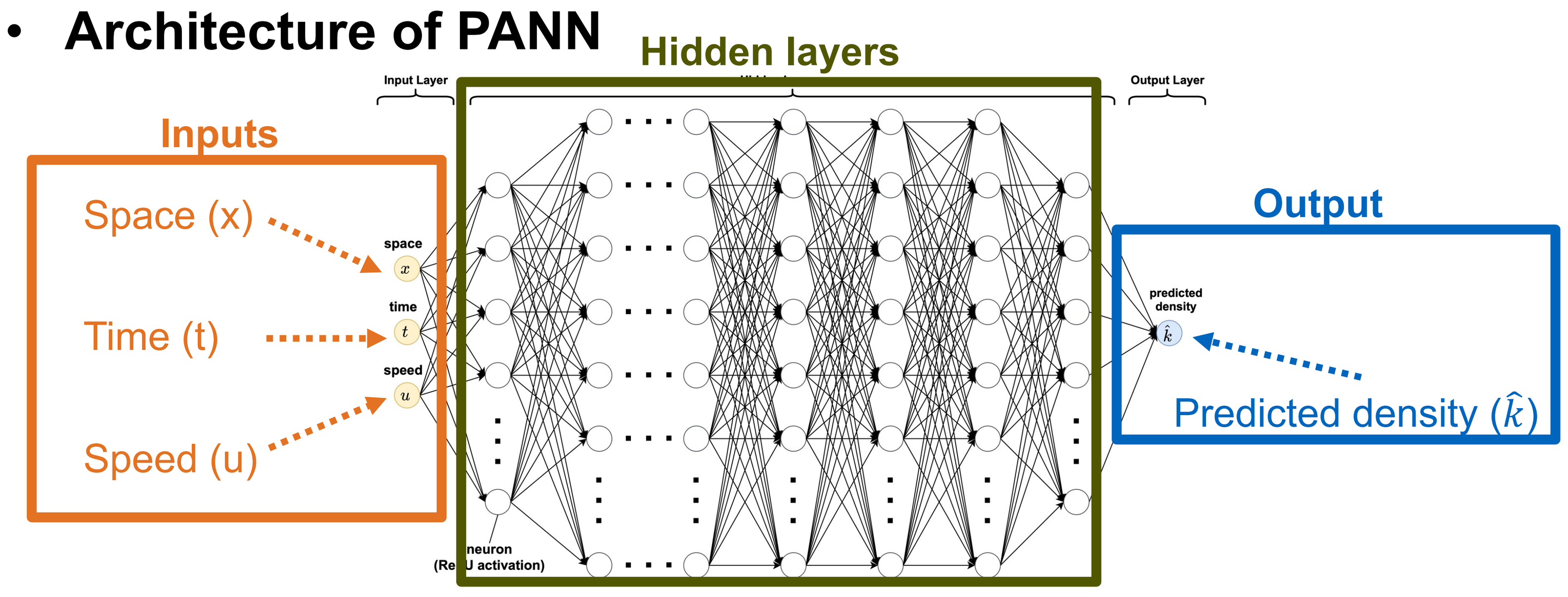
- **Model structure (1st order LWR model at merges)**

$$\frac{\partial k(x,t)}{\partial t} + \frac{dq(k)}{dk}\frac{\partial k(x,t)}{\partial x} = \begin{cases} \frac{q_{ramp}(t)}{L_{ramp}}, & \text{if x is within the merging zone} \\ 0, & \text{else} \end{cases}$$

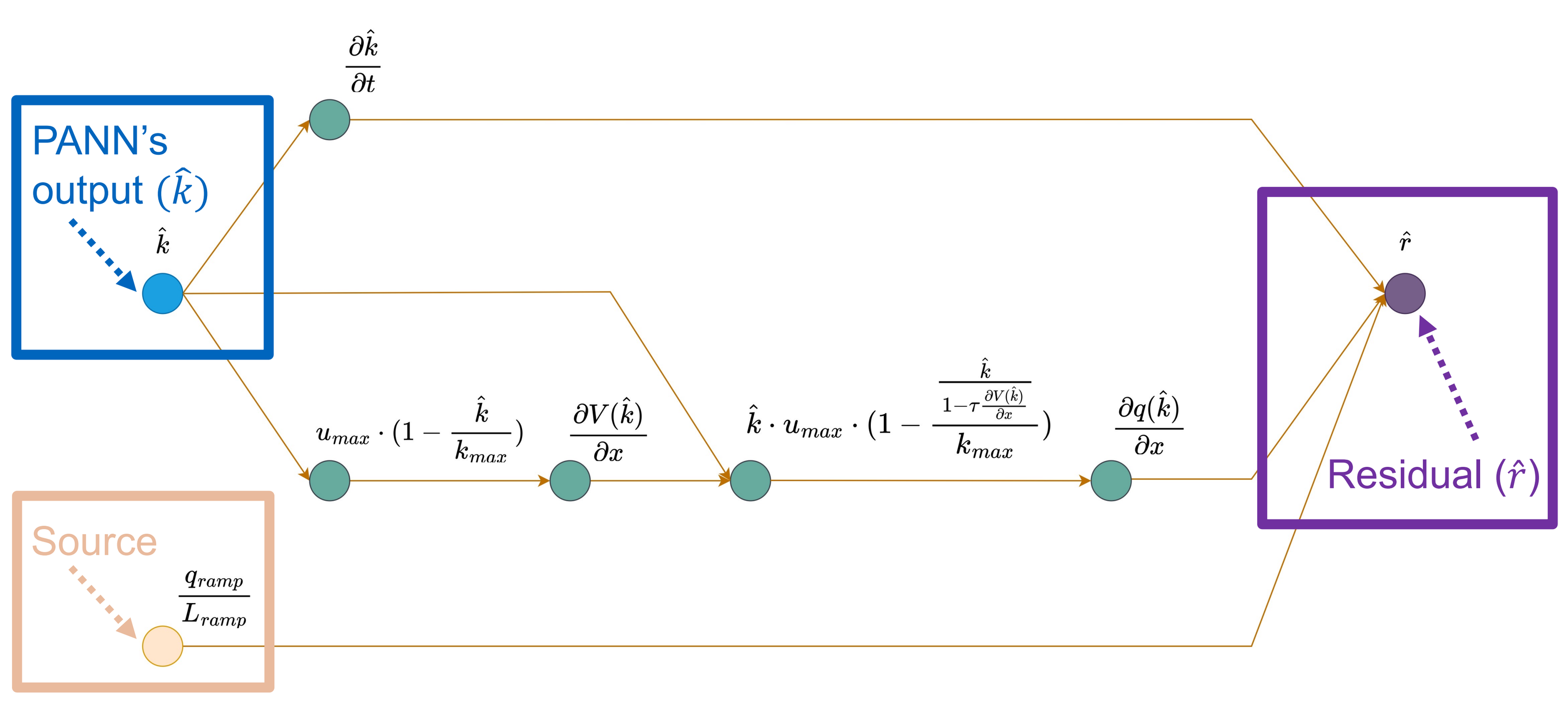
- **Working principle of PIDL**



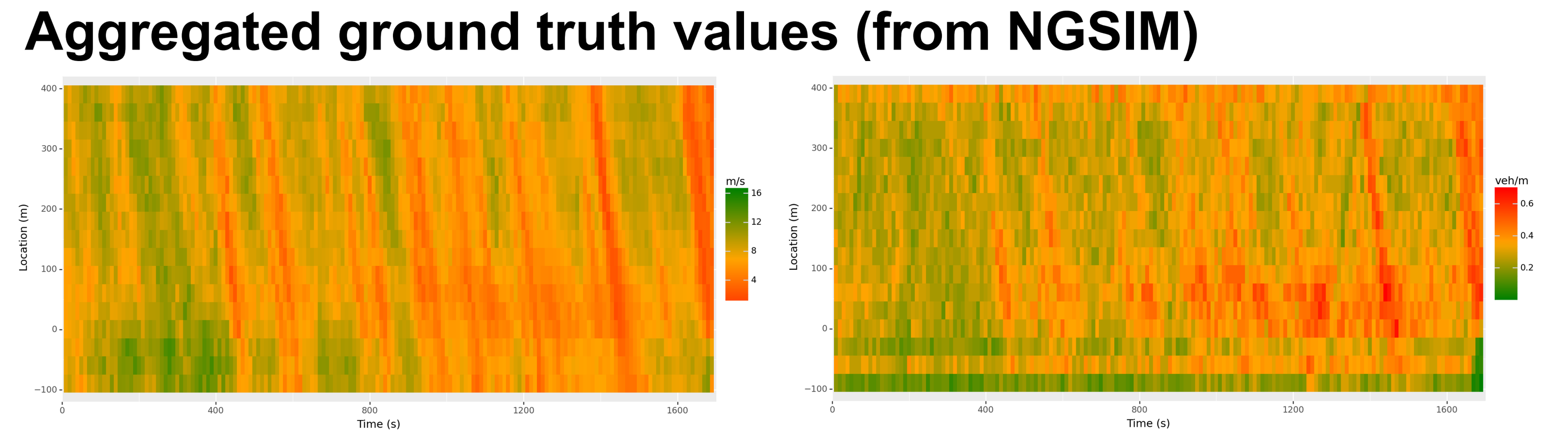
- **Architecture of PANN**



- **Architecture of the extended PINN with a delayed model**



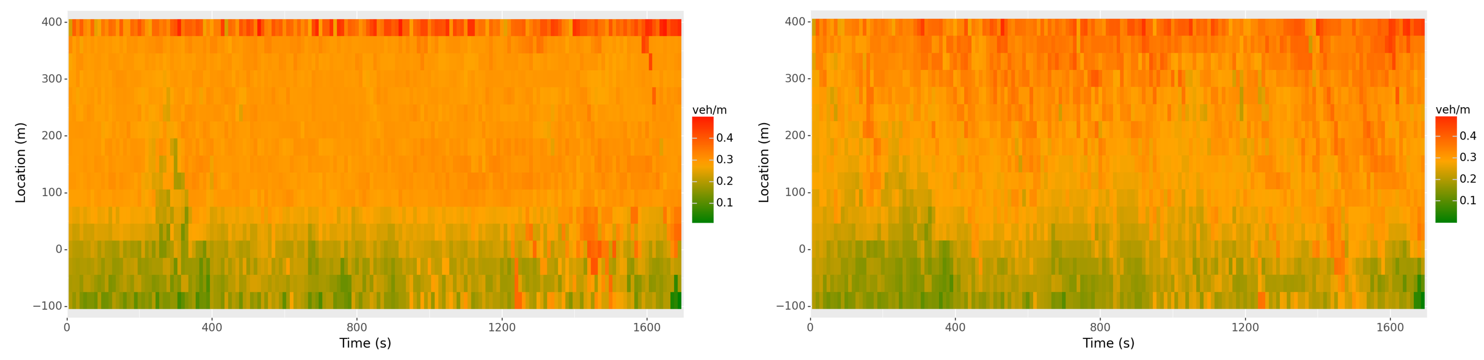
- **Aggregated ground truth values (from NGSIM)**



Spot speed | Density

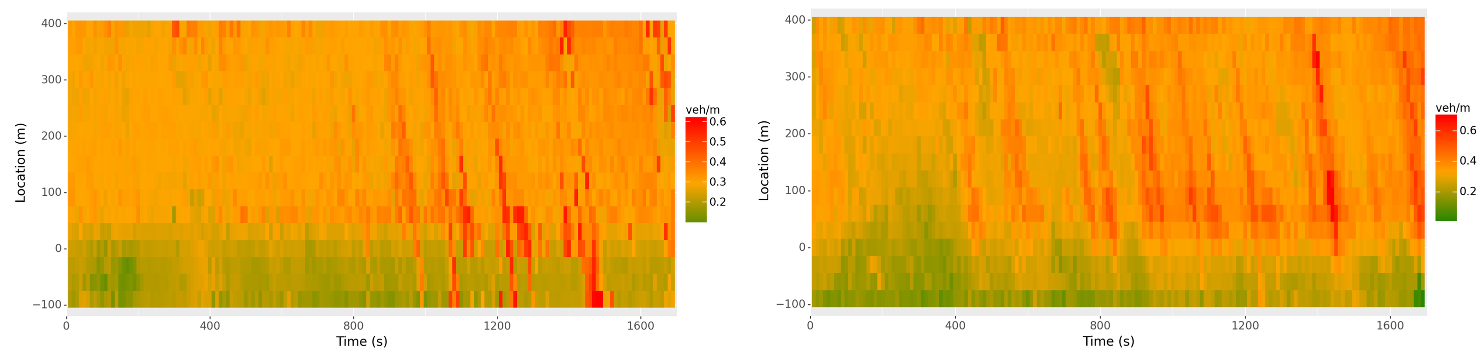
Density reconstruction results

Case (a), with stationary detectors at -90m and 390m



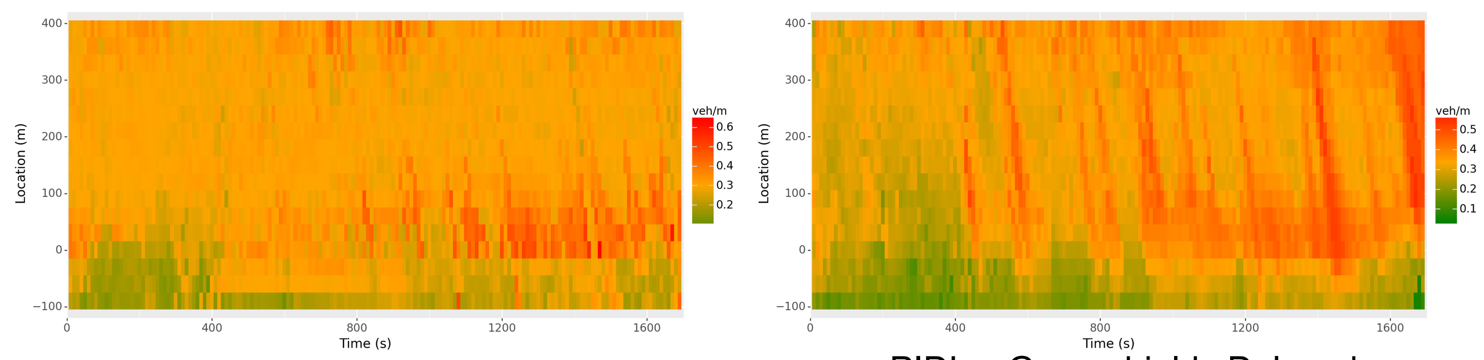
PIDL – base Greenshields | PIDL – Greenshields Delayed

Case (b), with stationary detectors at -90m, 60m and 390m



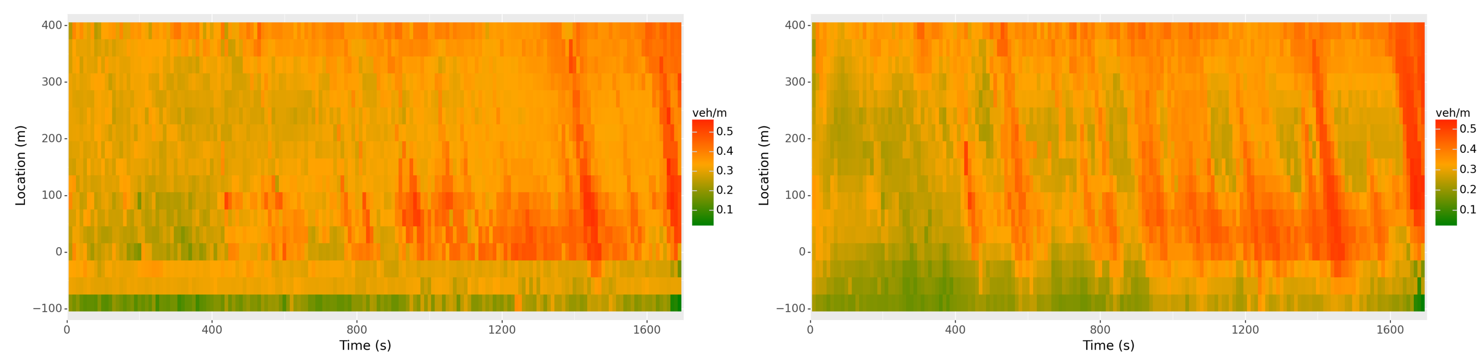
PIDL – base Greenshields | PIDL – Greenshields Delayed

Case (c), with stationary detectors at -90m, 0m, 90m and 390m



PIDL – base Greenshields | PIDL – Greenshields Delayed

Case (d), with stationary detectors at -90m, 0m, 90m, 240m and 390m



PIDL – base Greenshields | PIDL – Greenshields Delayed

In general, there are no meaningful reconstructed patterns with only two fixed detectors in case (a) by both PIDL methods. However, when an auxiliary merge detector at x=60m is used, there is a mass increase in prediction accuracy of the Greenshields Delayed model. Multiple S&G waves with increased density at the merging zone are clearly reflected in the Greenshields Delayed model. Still, the base Greenshields model tends to smooth out and dampen the S&G waves due to its homogeneous traffic assumption. When the number of fixed detectors increases, the Greenshields Delayed model shows higher improvements than the base Greenshields model which still exhibits gross smoothing even when sufficient observations are given. In the end, the Greenshields Delayed model is more robust than the base Greenshields model especially when limited number of detectors is available. Moreover, the additional input feature of PANN: speed (u) sampled by FCD aids PIDL models to quickly capture and understand S&G wave propagation behaviours, and easily edge out PIDL models which are trained with two input features: space (x) and time (t) only.

Limitations and outlook

An extended PIDL approach based on the conventional Greenshields-LWR model shows robust performances in density reconstruction through data fusion of loop detectors and FCD. Nevertheless, this thesis adopted a uniform placeholder value to fill in the unknown speed profile in FCD-free regions which inevitably introduces biases to deep learning models. Moreover, the current PIDL architectures are based on the Greenshields model that tends to overestimate the critical density that separates the free-flow and congested zone. Therefore, future work could focus on improving speed interpolation by low frequency FCD and testing PIDL based on other continuous traffic flow models such as Newell and Franklin. More could also be done on studying the optimization processes of PIDL which could lead to higher model accuracy and faster convergence rate.