Use of Neural Networks to Rapidly Quantify Impacts of Earthquake Disruption in Transportation Networks

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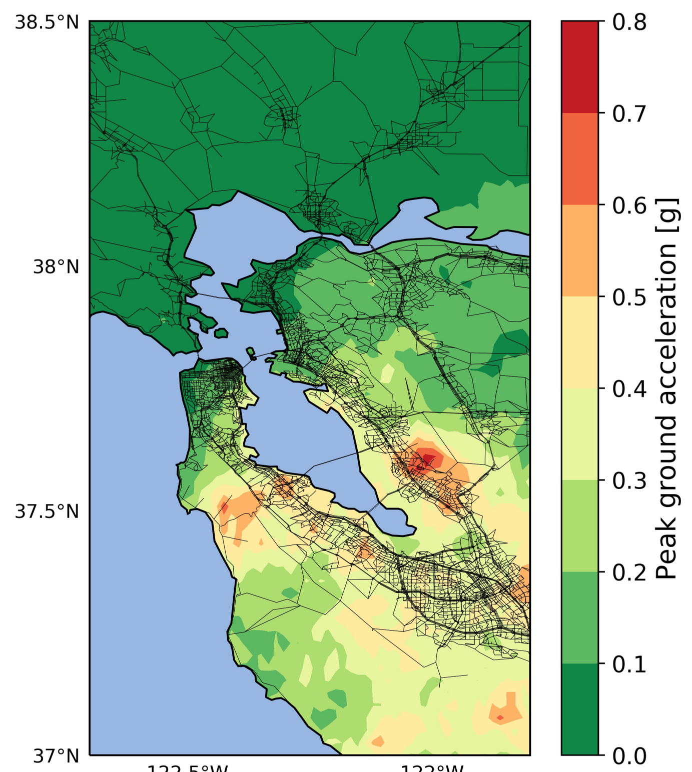
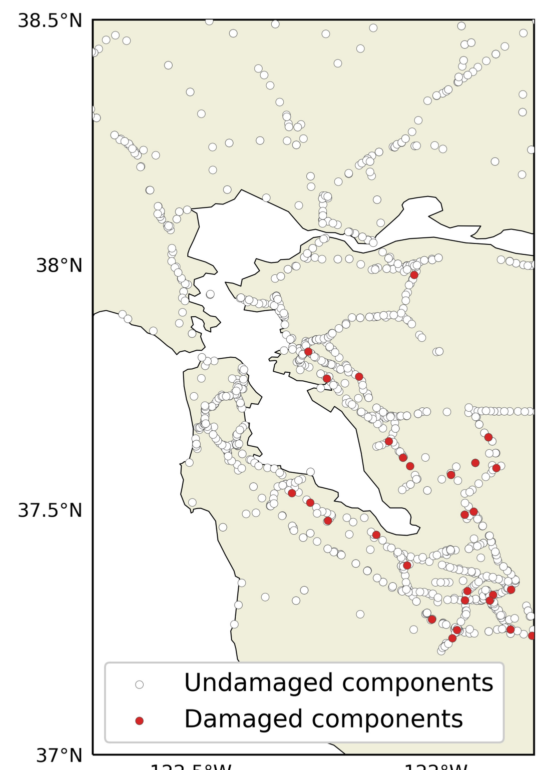
Motivation

Earthquakes are one of the most destructive forces of nature. Transportation networks are a fundamental part of cities and communities, allowing them to develop and function normally. These networks are composed by elements such as bridges and roads that can experience significant damage under the effect of earthquakes.

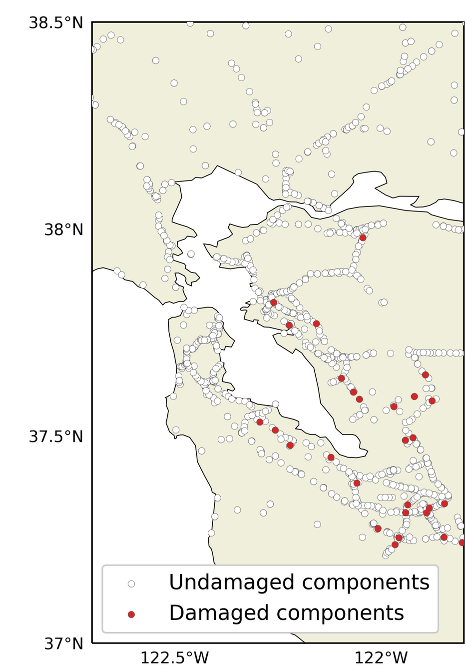


A) Ground Motion



B) Damage States

- In order to quantify the effect of a network disruption, the authors defined the Societal Traffic Loss (STL), which is a measure of the increase in time in transportation for all users.
- The **input** for this problem is the damage state of transportation network components.
- The **output** is the STL for that damaged network.



Input: Damaged Network

$$STL = \sum_{u \in Users} \Delta t(u)$$

$\Delta t(u)$: increase travel time of user u due to earthquake damage

Output: STL

Problem Definition

- In order to quantify the seismic risk of a transportation network, thousands of Monte Carlo simulations must be performed. Each simulation goes through the steps shown in the attached diagram.

Seismic scenario → Ground motion at sites of interest → Realization of damaged components → Traffic Assignment

- Among all the steps of the Monte Carlo simulation, most of the computation time is invested in the traffic assignment problem to compute travel times.
- The Iterative Traffic Assignment (ITA) model works in the following way:
  - For each pair Origin-Destination it computes the shortest path in terms of time.
  - Given the previous path, a fraction of the demand is assigned to it.
  - The times for each edge are updated using the formula:

$$t_a = t_f \left(1 + 0.15 \left(\frac{q_a}{c_f}\right)^4\right)$$

  - Where t_a is the time in the edge, t_f is the free flow time, q_a is the assigned flow in the edge, and c_f is its capacity.
  - The process is repeated until all the traffic has been assigned.
- ITA is computationally expensive, which restricts its use for seismic risk analysis of networks. Hence:

Our goal is to rapidly and accurately quantify the traffic disruption generated by damage over transportation network components.

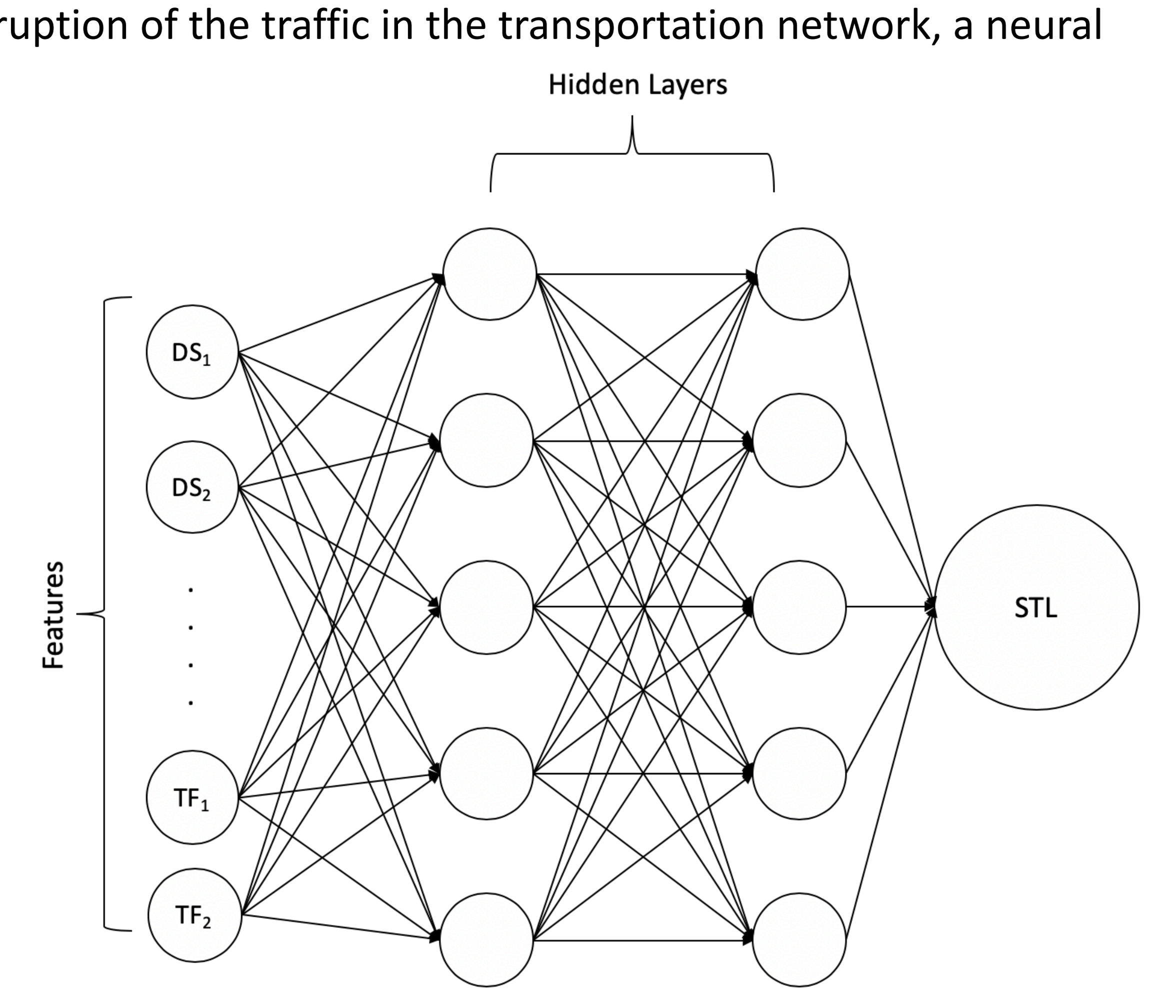
Approach

To rapidly quantify the disruption of the traffic in the transportation network, a neural network model is used.

Features (inputs):

Damage States (DS)

Topological Feature (TF):
- Katz centrality
- Degree
- Degree difference
- Capacity lost
- Maximum capacity lost
- Modularity difference



- The features are the Damage States (DS) of the components and Topological Feature (FT), which are properties of the disrupted graph.

Data

- The transportation network of the Bay Area were used to generate 10000 realizations of STL using the ITA model. Subsets of these simulations were used as the training (60%), validation (20%), and testing (20%) data.
- The graph of the network was provided by professor Jack Baker from his website. This graph is based on information from Caltrans and the Metropolitan Transportation Commission of the Bay Area (MTC).

Results and Analysis

To quantify the goodness of fitting of the results of the neural network, the coefficient of determination (R^2) was used:

$$R^2 = \frac{\sum_{\mathcal{D}_{val}} (y_{true} - y_{pred})^2}{\sum_{\mathcal{D}_{val}} (y_{true} - \bar{y}_{true})^2}$$

The hyperparameters of the neural network were selected using an exhaustive grid search.

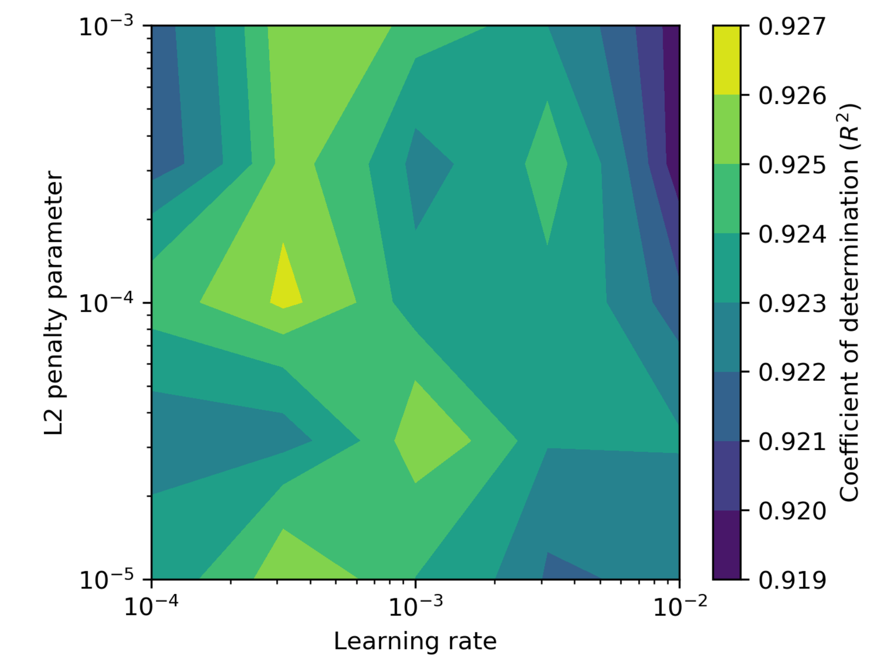


Figure A: Grid search plot for learning rate and penalty parameter.

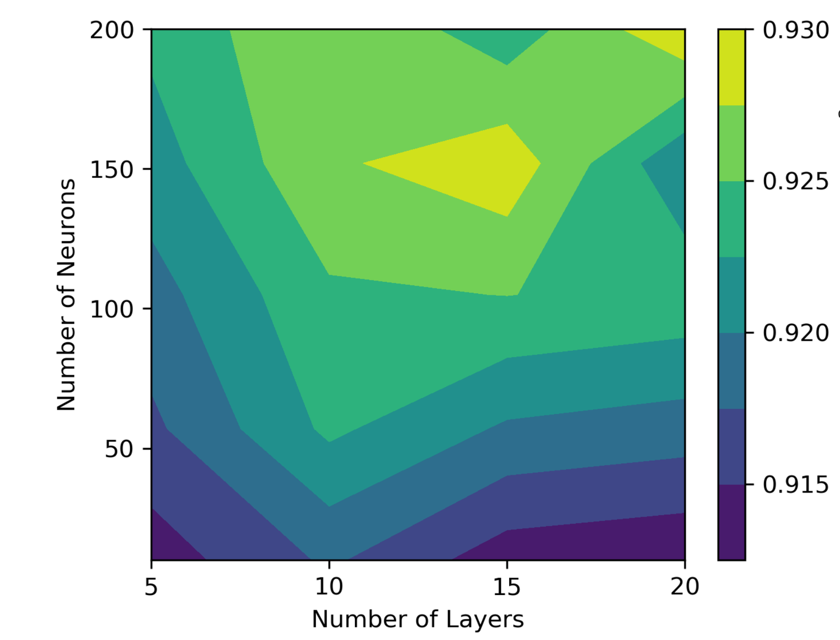


Figure B: Grid search plot for number of layers and number of neurons per layer.

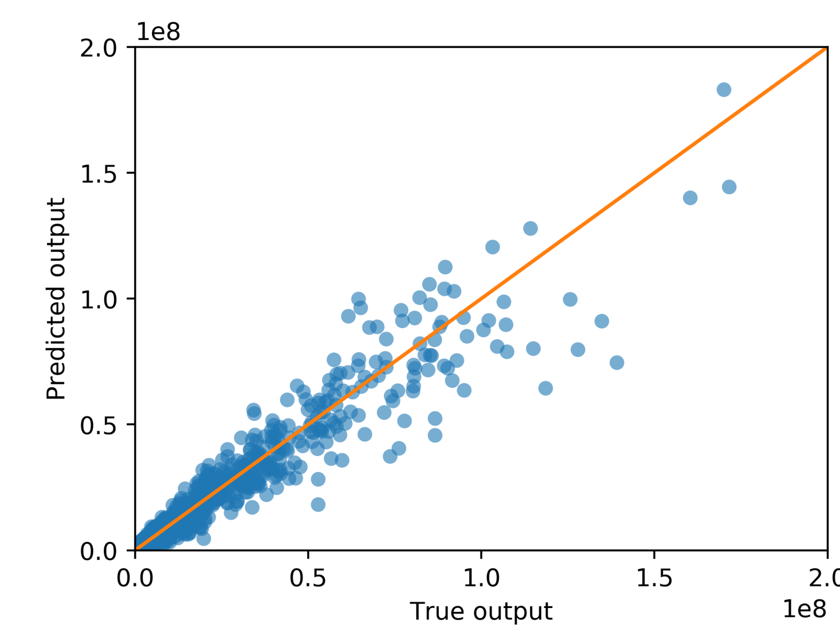


Figure C: Scatterplot of true vs predicted output.

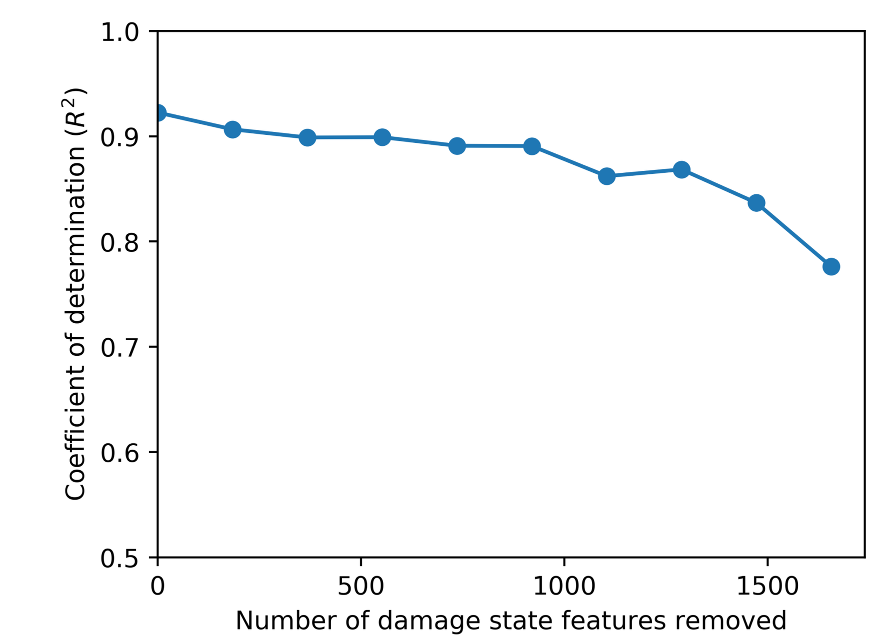


Figure D: Validation score as a function of the number of DS features removed.

Conclusions

As a summary, the following table shows a comparison of the predictor (neural network) with the oracle (ITA) and the baseline (ITA without congestion updates).

	Computation time	R^2	Mean absolute error (years)	Explained Variance score
Oracle	58.2 s	1.000	0	1.000
Baseline	17.7 s	0.868	324.6	0.868
Predictor	0.0004 s	0.933	228.5	0.934

- The predictor behaves more than a million times faster and accurately enough to make decisions in transportation networks.

Societal Impact: This research will be used to assess the seismic risk of transportation networks, which is used by decision makers to propose mitigation strategies, such as retrofitting bridges, to improve the resilience of the system against earthquakes.