

A flow network model to track Covid infection through time

Andrew Zhang, Jenny Wang, Raymond Wang, Hua Wang

Abstract

In this work, we modeled the spread of Coronavirus (COVID-19) in New England by representing the region as a flow network with multiple time periods, and then applying the Ford-Fulkerson algorithm with various improvements. We developed a new way to evolve the flow network between time periods by introducing the evolution node, which adds flow through an inflow node and subtracts flow through an outflow node. This allows us to adjust the flow in between time periods based on the factors of new vaccinations, new cases, and a travel metric. To support these adjustments, we modified the Ford-Fulkerson algorithm to handle minimum and maximum bounds on edge capacities as well as multiple sources and sinks of flow. We also modified the vaccination statistics of various states to identify where additional vaccinations would be most impactful. The results provided information that can be beneficial to infectious disease control and prevention.

Introduction

Given a directed graph with a source (a node with all edges directed out of it) and a sink (a node with all edges directed into it), the Ford-Fulkerson Algorithm allows us to find the maximum flow from the source to the sink. To represent the New England states as a graph, we consider each state as an individual node. Then, we create an edge between any two states if they have a land border. A graphical representation of this can be seen in Figure 1.

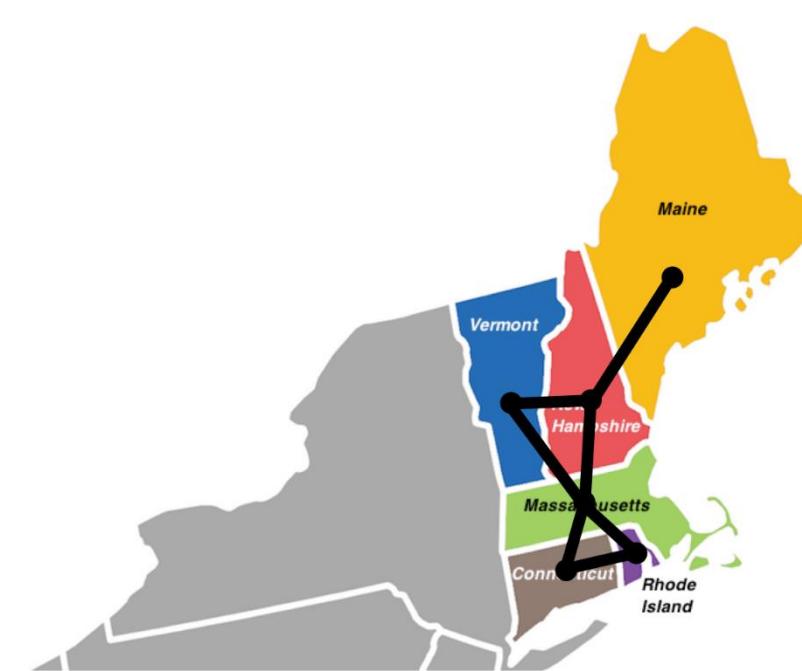


Figure 1. A graphical representation of New England

Methods

To simulate the flow of Covid over time, we extended the previous graph. First, we created a root node that from which all of the flow was sourced. This node connected to all of the states in their first time state. Then, after using the Ford-Fulkerson algorithm to simulate the Covid flow within these first six nodes, these nodes were each connected to a modification node. In each of these modification nodes, an additional source node created increased Covid flow into the

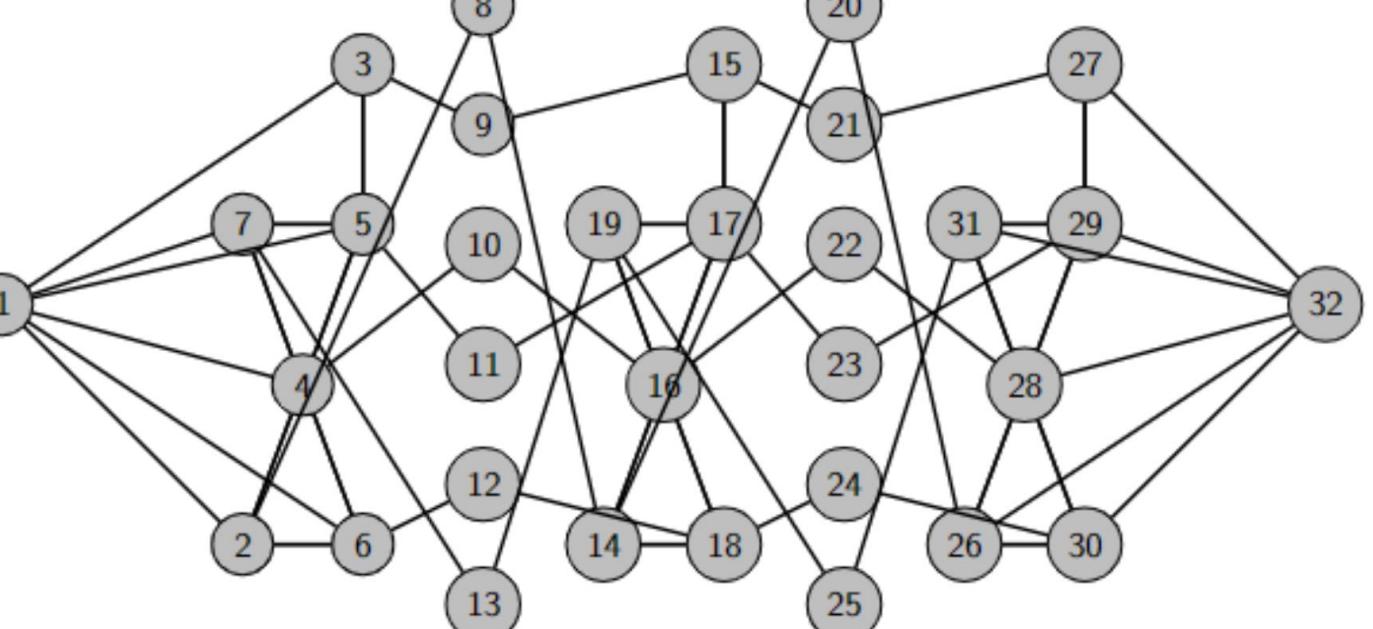
Methods and Materials

node based on two factors: the travel metric, and the numbers of deaths. These statistics were used as a measure of ineffective Covid prevention and healthcare within a state. Thus, they were used as modifiers that increased the number of COVID cases within a state in the evolution nodes. To find the travel metric, we considered the number of trips taken in a state for several mileage ranges. Then, we attached a weight for each of the categories of length with longer trips given higher weight and shorter trips given lower weight. We then summed all of the weights and normalized the total sum to create the travel metric. The death metric was simply created by normalizing the numbers of deaths according to the state population.

Additionally, for each modification node there is an additional sink node, which takes flow out of the modification node. This is based on the vaccination rate, which was used as a positive indicator of effective healthcare within a state. To find the vaccination metric, we summed the vaccination statistics for the past six months and normalized that sum with the population of the state. After the flow for each state goes through modification, we output the predicted Covid cases for that time state. Then, this flow is rerouted into another set of six nodes which again represent the geographical representation of the six New England state. In Figure 2, the model is shown graphically. The nodes 1-6 represent the state nodes while the nodes 8-13 represent modification nodes. The actual source and sink nodes that edit the modification nodes are not shown.

By continuously running this process, we were able to generate a prediction for the amount of Covid cases in the New England states over several time periods.

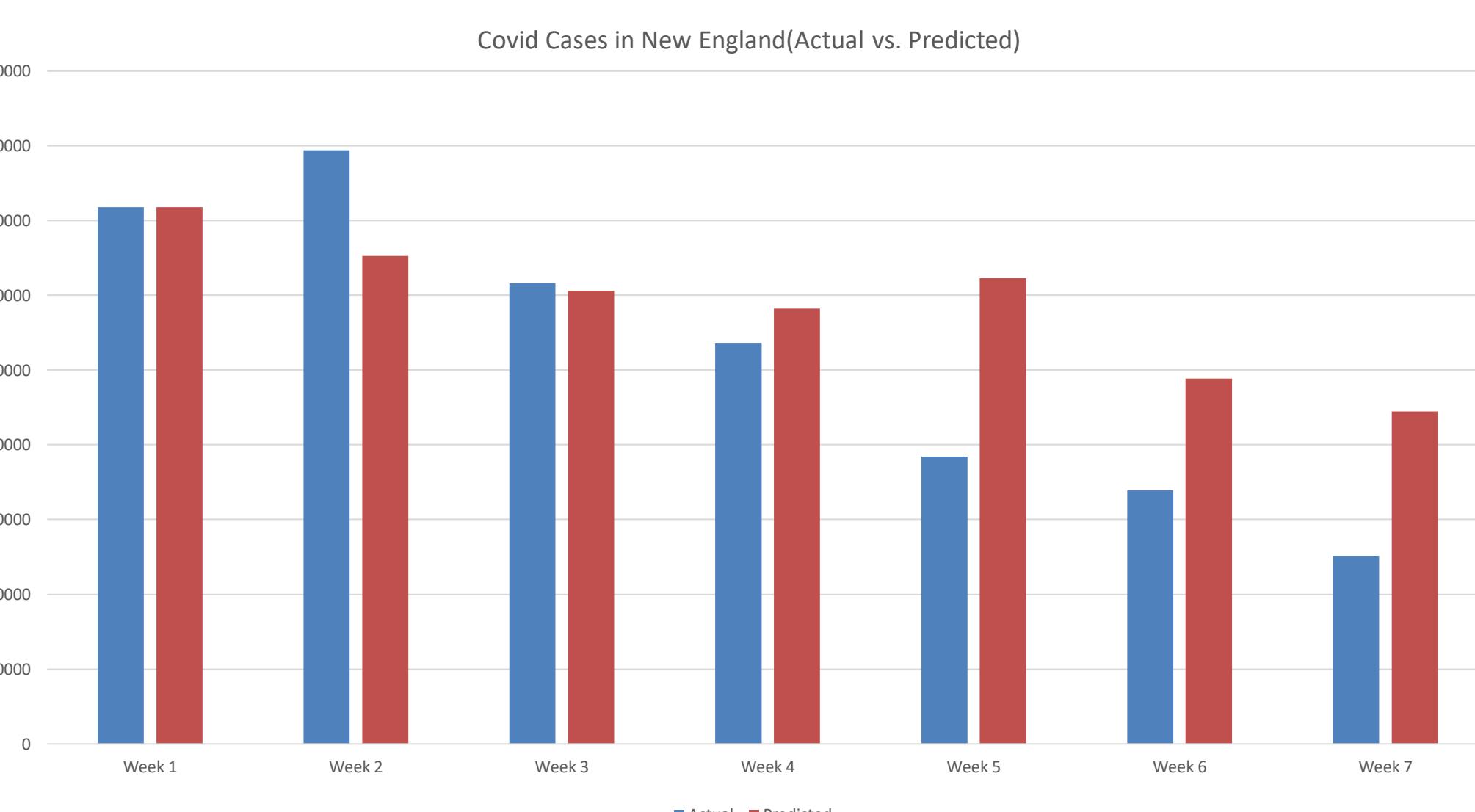
Figure 2: A graphical representation of the model



Results

We used the model to analyze the flow of Covid 19 over time. First, we simulated the model over the first 7 weeks. For the first week, we set the flow to the nodes of each equivalent to their amount of cases during the first week of 2021. Then, for each successive week, we input the data for the vaccination rates, death rates, and travel metric for the previous week. The model then predicted the expected Covid cases for the next week by editing the flow of Covid using the provided statistics and another run of the Ford Fulkerson algorithm. The results of this simulation are shown in Chart 1.

Chart 1. Predicted vs Actual Covid Cases.



The second part of our investigation was designed to measure the effect of adding 5,000 additional vaccinations to a certain state for each time state. For each simulation, we added 5,000 extra vaccinations to a specific state for each time state. Then, the numbers of Covid cases at the end of the simulation for all states were summed. This value was compared to the total number of Covid cases in a simulation with unaltered data. This comparison allowed us to determine the number of Covid cases that could be prevented in New England through additional vaccinations in just one state. The resulting amounts of Covid cases prevented through additional vaccination are shown in Chart 2.

Contact Information

Andrew Zhang
Wayzata High School
Email: andrewzhang05719@gmail.com
Phone: 763-283-6954

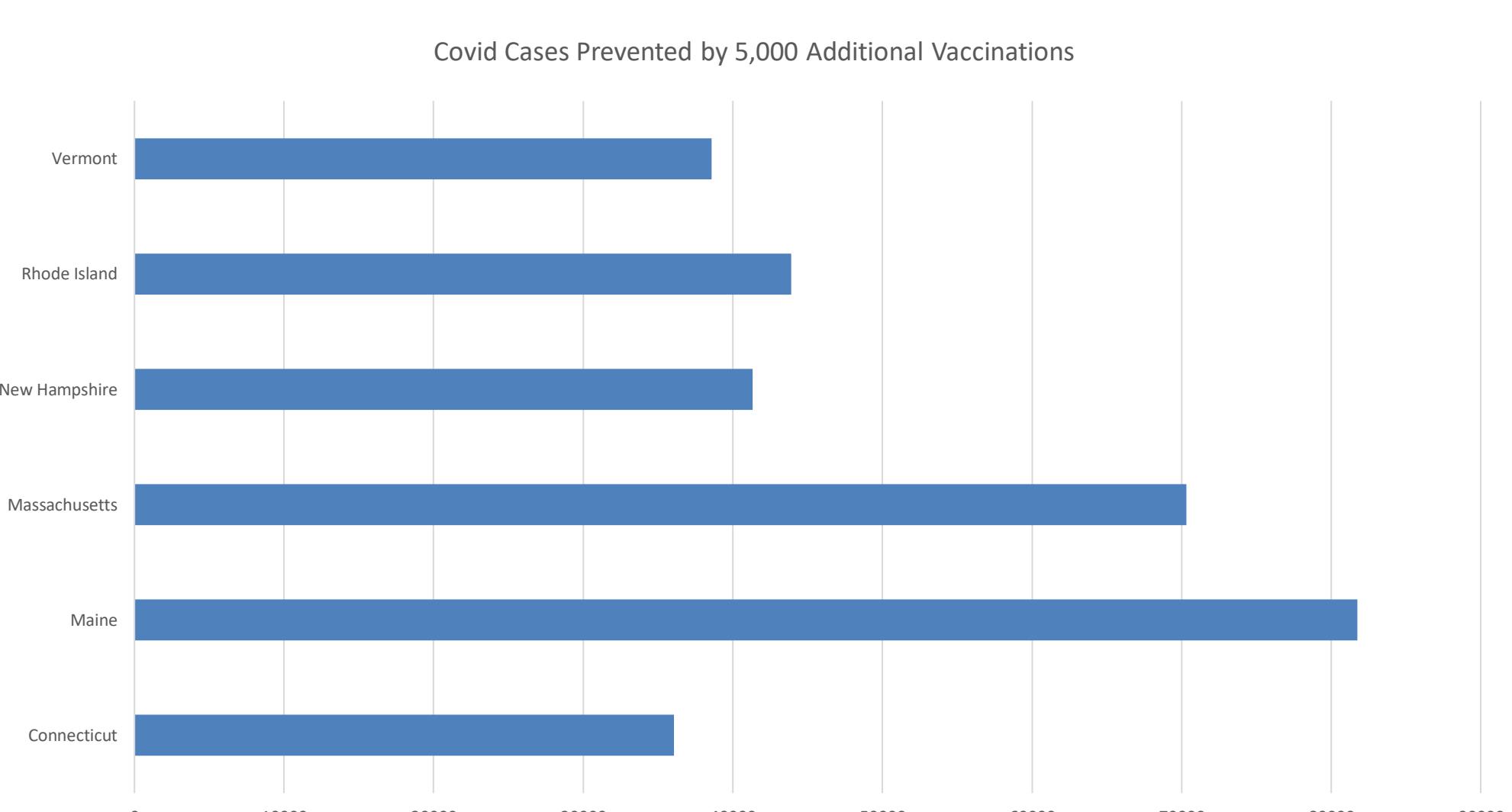
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Chart 2. Covid-cases cut by increased vaccination



Conclusions

We see that the model can generally predict the trends of Covid cases across several time periods. However, it does have a tendency to spike up in certain time periods such as week 5, perhaps due to one of the three variables being weighted inaccurately. In regards to the covid cases prevented through vaccination, we see that the top two states are Massachusetts and Maine. Maine being the state where the additional vaccinations would have most effect is likely due to the fact that Maine had a relatively high death metric. This indicates poor Covid prevention and health care which meant that the modifier node was fed a lot of extra cases through a source node. Massachusetts being the second highest is likely due to it being connected to four other New England states. Thus, reducing infection in Massachusetts also has a positive preventive effect on other states.

Future Directions

In the future, we aim to add a factor that accounts for how transmittable a certain virus is. This will allow us to expand this model to other diseases beyond Covid-19. Additionally, to more accurately model the spread of disease, we will add air routes between states that do not share a land border. These air routes would need to have a lower capacity due to the limited traffic that airports can handle. Finally, to precisely simulate the impact of vaccines on virus transmission, more data analysis on the effectiveness of vaccines in relation to the percentage of the population that is vaccinated is likely necessary.