

A simulation framework to evaluate efficiency and safety of public transportation systems during pandemic

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Abstract

With the spread of the SARS-CoV-2 virus, the return to operations for schools, workplaces, and other work-life related activities has been largely affected by social distancing and other pandemic containment policies. System operators need to consider potential virus spread to reduce infections, while ensuring operational efficiency. This is particularly important for public transit services that form social hubs and possible hotspots for the spread of virus. In this paper, we develop a simulation platform to validate the design of routes and bus schedules for a large university's transit system. We use an agent-based model to track the operations of buses, as well as the quality of service provided to each passenger and estimate their exposure to a contagious virus. Our results show that the redesign of a traditional system into a Hub-and-Spoke design can improve operational efficiency with the same number of vehicles and reduces possible infections inside buses by reducing consecutive in-vehicle travel time for all passengers.

Keywords

Bus route design, Hub-and-Spoke, agent-based simulation, COVID-19 pandemic

1. Introduction

University of Monterrey (UEM) locates in a metropolitan area, comprising the most populated cities in the country of Mexico with an approximate population of 5 million inhabitants spreading over 300 square kilometers. The main transportation mode of all the students, faculty and staff in UDEM is private car, followed using traditional taxi cabs and on-demand ridesharing services [1]. In smaller proportions, collective options are available for UDEM's affiliates to use. Circuit UX is a free-for-students collective transportation system that works with an app in which students book their trips and can get expected time of vehicle arrival and availability of different vans, each having a capacity of up to 40 passengers. However, routes in Circuit UX are usually long loops that can take more than an hour for a round trip. The reduction of passengers' wait time in the system requires the addition of more buses to increase the frequency of buses cycling through the routes, but this can yield high financial burdens for the University and is not realistic [2].

Since the COVID-19 pandemic took place, UDEM's bus system has been inactive as the campus remained closed following the government's guidelines. As population vaccination rates increase, the possibility of a return to activities at a 50% capacity for university classrooms and transportation systems is a matter of time. Zhang et al. [3] simulate aerosols dispersion in a United States' university's bus system to show that riding longer than 15 minutes with an infected passenger drastically increases other passengers' exposure to the SARS-CoV-2 virus and their probability of infection. The current routes provided by Circuit UX all exceed the 15-minute threshold and thus need to be redesigned to minimize unsafe travels. (The shortest route is 40 minutes and the longest can take up to 80 minutes, not considering passenger transit or waiting time.) In this work, we use the mathematical optimization model proposed by Chen et al. [4] to make a Hub-and-Spoke design of bus routes for UDEM and develop a simulation platform to evaluate its performance during pandemic. Our goal is to not only increase the efficiency of bus operations, but also to limit the number of potential passenger infections.

2. Literature Review and Comparison

The Hub-and-Spoke is a design that proposes a different use of vehicle capacity in transit systems and the trace of connecting routes. Like how airplane routes are traced, the identification of hubs that attract significant amounts of traffic to certain locations are the main locations from which other less traveled routes, or spokes, connect. In this way, the total transportation needs can be redistributed to adapt to the spatial disparity of demand and has proved efficient. Campus transportation involves demand clusters between dorms (residential zones) and classrooms, and thus they can be potentially well-satisfied using a Hub-and-Spoke design [5]. Kim & Soh [6] propose a Hub-and-Spoke transit system for Won Kwang University in South Korea, using a p-median model. However, they did not test and

validate the design, and one of the contributions of this paper is that we program a tool that can validate route designs to identify the feasibility and convenience of a given transportation system.

During the pandemic, due to social distancing requirements, one needs to reduce the number of passengers who share their travel time in the same vehicle and use less vehicle capacity to satisfy normal demand [3]. Therefore, without increasing the number of vehicles and their frequency, a Hub-and-Spoke design can become a possible solution as it requires passengers to transfer routes more frequently but will reduce the time traveling in the same vehicle, which is essential to control the spread of a virus [7].

Simulation is a helpful approach for the validation and testing of infection control in a system. For example, Müller et al. [8] develop a multi-day simulation of a population group and focuses on the SIR, S = Susceptible, I = Infected, and R = Recovered, model to understand the differences between using private cars and public transport, considering that infections can take place on multiple activity centers and then spread in public places. Our model does not consider multi-day infections, neither what happens after the passenger exits the simulation, but rather we focus on explaining how different route designs on the same transportation system can have impact on the spread of infections and whether they can still satisfy the original demand well, which is not explained in Müller et al.'s [8] work. Another COVID-19 infection tracing work by Fang et al. [9] develops a model to simulate the Diamond Princess cruise disease propagation. They use a space-continuous, agent-based simulation to test protection measures effectiveness. Our work contributes by not focusing on one single vehicle or one population group, but rather on a network of transit services, by measuring not only the infections, but also several operational efficiency and quality of service measures that are of interest to both system operators and passengers who use the system. Our work is closely related to a prior work on redesigning the University of Michigan's campus bus system during the pandemic (see, e.g., [4]). We apply their mathematical model to optimize routes for another university having different demand and develop a contribution of an agent-based simulation platform that can trace virus propagation and can serve as a tool to test different instances of transportation systems.

3. Redesign of UDEM's Campus Bus System

We present the redesign solution generated with the mixed-integer programming model proposed by Chen et al. [4], which minimizes the total number of routes operated and travel time of all routes, to design bus routes that connect to hub stops. As a result, from the application of the optimization model, the two long routes used in current UDEM's bus system were divided into three hubs, seven routes, and one hub connection route. **Table 1** compares the original system and the generated Hub-and-Spoke design, with a noticeable reduction in the number of stops. **Figure 1** shows the original trace of routes being distributed for the east and west of UDEM's campus located at the black dot, and **Figure 2** shows the proposed Hub-and-Spoke system trace with routes being distributed around the three hubs located at the black dots.

Table 1: The Traditional and Hub-and-Spoke designs to be compared

Characteristic	Traditional	Hub-and-Spoke
Number of Hubs	0	3
Number of routes	2	7 spoke routes and 1 hub connection route
Number of stops	50 (29 and 21 for each route)	23 stops (5, 13 and 4 for each hub)

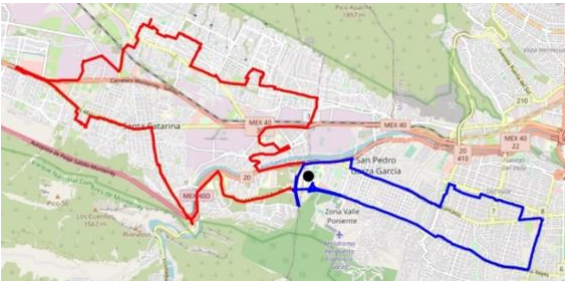


Figure 1: Current UDEM's campus bus system

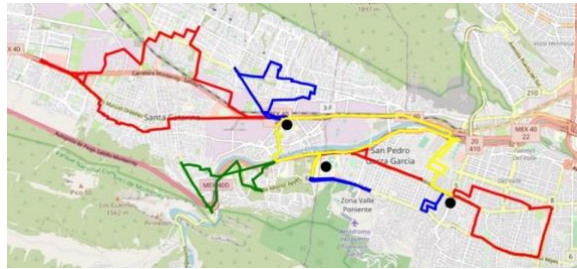


Figure 2: A new Hub-and-spoke design

4. A Simulation Platform to Evaluate Route Designs

We test and enhance the design of the routes generated by the optimization model using a discrete-event, agent-based simulation model. The MESA simulation package for Python is used to program the simulation platform [10].

Passengers and buses are modeled as agents. Bus stops are modeled as python dictionaries that store the variables for each location. Buses moving along routes follow a logic that dictate their possible locations.

Simulation setup: The simulation begins with **buses** being inserted on their hub depending on their specified starting time and designed routes. When the time between stops has passed, a bus will be available to ride as its ID is appended to the bus stop dictionary list of available buses. The bus will wait one simulation step (one minute of real time) for users to ride it if the bus matches the user's travel need to a specific route and sense (clockwise and counter clockwise if sufficient buses are destined to the route). The bus reports its current capacity and if it is not full, then the user can ride the bus. Then the bus will leave the current stop removing itself from the stop dictionary and removing the users from the stop dictionary until the travel time for the next stop has been completed, repeating this operation until the simulation time ends or the bus operation time ends.

Users in the simulation are inserted on their specified initial time and will have an origin and destination assigned. As users enter the simulation at their origin stop, their transfer plan for the shortest time to arrive to the destination will be generated and users will wait for a bus following the requested route and sense. On every transfer, a user can check once if there are any other routes (or senses) that given the current state of buses could decrease the travel time, and once decided the user waits in line for the requested bus. The user repeats this operation until they reach the destination stop and the user exits the simulation. To simulate the infection spread, users initiate with a binary state of initially infected or not, and when infected, if the user spends equal or more time than the infection threshold, other users that have also spend more time in the threshold will be subject to get infected in buses depending on the infection success percentage that is given as a simulation parameter, simulating that not all users in the bus will get infected, but only a proportion of those on board. **Figure 3** shows the flow of data and processes that run the simulation.

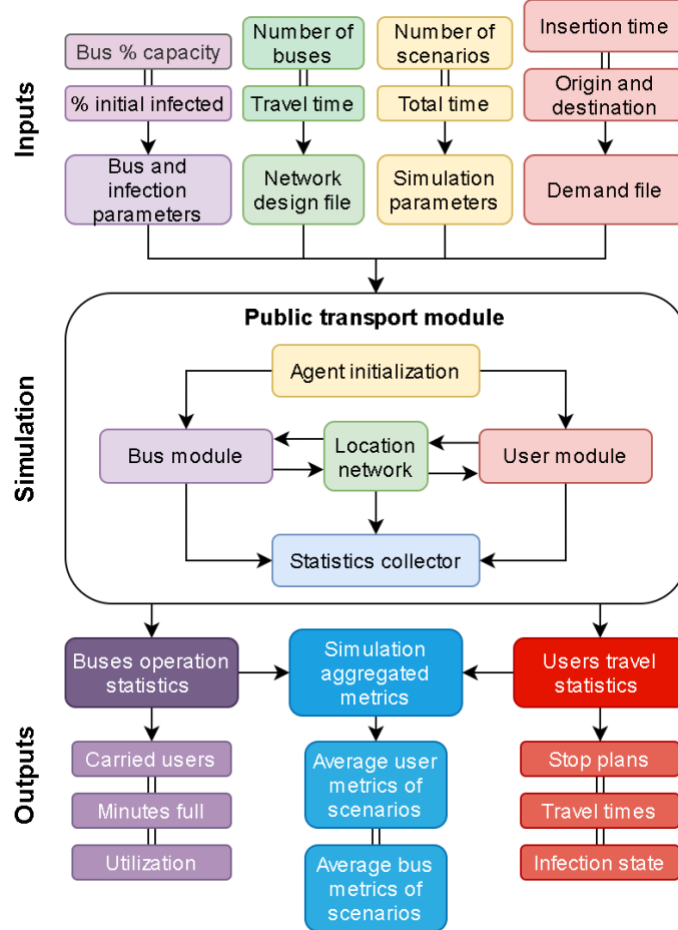


Figure 3: Flow diagram of simulation platform

Input files: As described in **Figure 3** four inputs are required by the simulation platform: (i) Parameters indicating percentage of available capacity of a bus and percentage of initially infected users to be simulated. (ii) The network design that describes all routes for each hub region, including for each leg of the route the origin stop and destination

stop, the forward and reversed sense travel time and the number of buses available for each route. (iii) The total time of simulation that will determine the operation length of buses and insertion of users in the simulation, as well as the number of scenarios to run to test the variations between different patterns of demand. (iv) The demand file includes the number of users that will be simulated with their respective insertion time and their initial plan to get from the origin to their destination stop. This file is generated by defining origin-destination relative demand and randomly generating trips from origins to destinations until the percentages are met, repeating the process for the definition of insertion times of users. If several scenarios are simulated, the variations in the demand pattern will be produced by the iteration of the demand generation process, once for each requested scenario.

Simulation output: After the simulation of the transportation system operation is finished, three files are generated: (i) A file that stores for each user in the simulation their stop plan, travel and wait time, time for each leg of the trip and infection state after leaving the simulation. (ii) A file storing for each bus with information about the carried users, minutes full, average utilization and on board infections. (iii) A file that stores the average value for the recollected files for users and buses for all scenarios that were simulated.

5. Results and Analysis

We present the results of the proposed Hub-and-Spoke system in comparison with the traditional routes in Circuit UX, showing the benefits of a Hub-and-Spoke design in terms of operational efficiency and on virus propagation control.

Test configuration: Following the description of simulation setups in [Section 4](#), [Table 2](#) shows common parameters that both the traditional and the proposed system's simulation models will be setup with, in which four demand levels and two bus capacity levels will be considered. The combinations of these parameters sum to eight scenarios for each system. The parameter of infected bus riders when the exposure time exceeds the threshold is used to simulate that only a subset of passengers in the bus will get infected (e.g., at 50%, half of the bus in closest contact with an infected passenger is infected or at 100% all users in the bus will get infected). In this configuration, the percentage of susceptible users is 90% and 10% will be inserted on different steps with the ability to infect other passengers.

Table 2: General parameters for simulation scenarios

Parameter	Value
Total simulation time	960 steps (minutes)
Number of buses	16
Full capacity of buses	40 passengers
Bus capacities	50% and 100%
Time in bus threshold for infection	15 steps (minutes)
% of initially infected users	10%
% of initially infected users in bus when threshold exceeded	50%
User demand levels	500, 1500, 2500, 3500

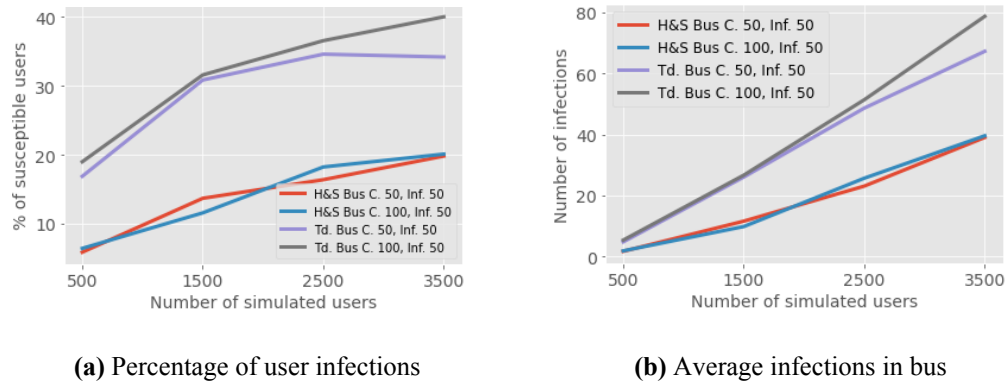


Figure 4: Infection metrics

Analysis: From the simulation of the eight scenarios of the traditional and Hub-and-Spoke systems, we show the performance of both systems and benefits of using the Hub-and-Spoke design. [Figure 4a](#) shows that at every demand level, the traditional system has significantly higher percentage of infections, approximately double the infections of

the proposed Hub-and-Spoke system. Note that at high demand levels, the policy of 50% capacity helps reduce infections in the traditional system. Similarly, **Figure 4b** shows that the average infections in each one of the 16 buses in the system is greater at all tested demand levels in the traditional system, but as demand grows, the difference between the two systems is more significant. The proposed system's infections are rather similar at different bus capacities and not necessarily get improved with capacity reduction policies. And thus, the Hub-and-Spoke system is better at infection containment than the traditional system at all demand levels.

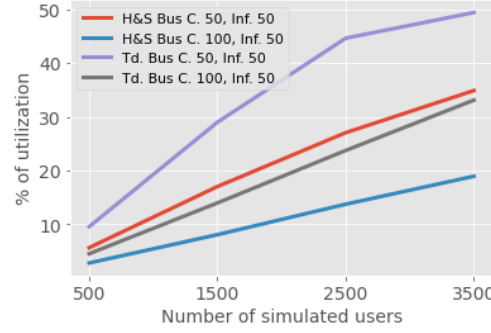


Figure 5: Average utilization of buses

Figure 5 shows that buses present higher utilization (i.e., buses carry more passengers, more time) at 50% bus capacity policy, even so that the traditional system with 100% capacity has lower bus utilization than the Hub-and-Spoke design at 50%, and therefore can transport most demand without purchasing new buses. The benefits of the efficiency grow as the demand increases, and therefore, the Hub-and-Spoke system becomes more efficient at higher demand levels.

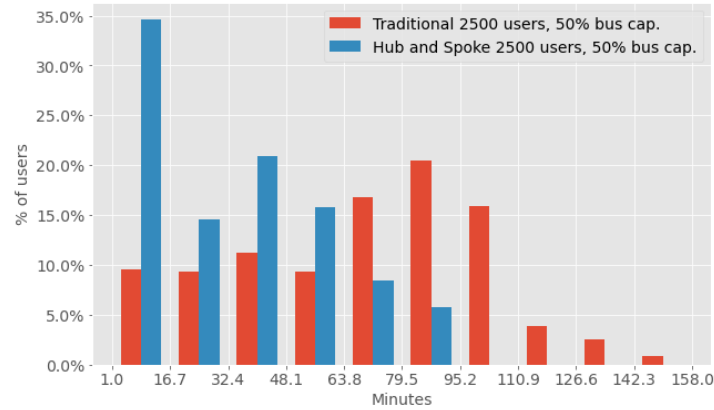


Figure 6: Users' travel time

We plot histograms to compare the distribution of metrics for users and buses for two of the tested configurations (demand of 2500 users and 50% bus capacity policy) for both systems. **Figure 6** indicates that in the Hub-and-Spoke system, 35% of passengers spend at most 16-minute in-bus time in total to get from origins to destinations, and only 15% spend over an hour traveling in buses, satisfying the requirement of 15 min. By the contrary, approximately 60% of all passengers in the traditional system spend more than an hour in buses, which shows the reduction in travel time brought by the Hub-and-Spoke design, with an increase of the number of transfers from an average of 0.2 transfer in the traditional system, to a 1.2 average transfers in the proposed system.

Figure 7a shows that in both systems, half of the buses spend less than 80 minutes full, while in the traditional system, all other buses spend at least 564 minutes full, and in the Hub-and-Spoke system the remaining 45% of the buses spend less than 241 minutes full and 5% of the buses (i.e., only one bus) spends about 500 minutes full. 50% of buses in traditional buses spend from 560 to 800 minutes full (out of 960 minutes). **Figure 7b** shows that the buses in the Hub-and-Spoke system have less infections per bus, and only 30% of buses have between 80 and 130 infections, and more than 40% of buses in the traditional system have between 130 and 190 infections per bus. This shows that the Hub-and-Spoke system operation and infection situation are both better than those of the traditional system. Furthermore, these metrics can help identify specific buses or routes that could be generating infections at a higher

rate. We can further redesign to shorten those routes, add a new stop or reiterate the simulation process to find better solutions.

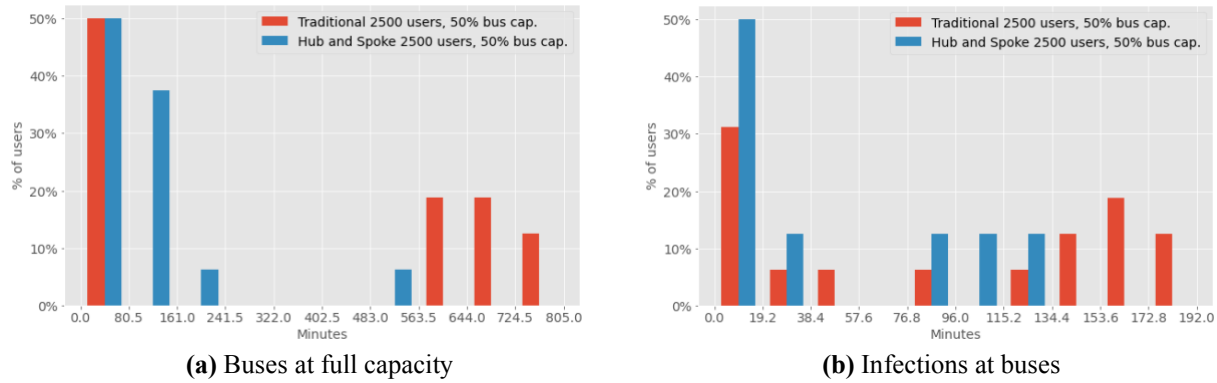


Figure 7: Buses' operational metrics

6. Conclusion

We developed a simulation platform as a tool to compare different transportation systems and configurations by their operation or the effectiveness to control the spread of virus, proving helpful in the process of route design enhancement and testing. Beyond university transportation systems, this tool can be used for other transportation systems that have similar characteristics. Due to data unavailability, some limitations include not considering uncertain travel time, nor demand pattern variations by day of the week and by hour. Additionally, the simulation platform could be modified to include metrics to evaluate other system operation aspects.

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