Center for Advanced Multimodal Mobility Solutions and Education

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COUNTERMEASURES FOR MAINTAINING SAFE AND EFFECTIVE PUBLIC TRANSIT SERVICE IN THE POST-COVID-19 ERA

Final Report

by

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EXECUTIVE SUMMARY

During the COVID pandemic, to prevent the spread of the virus, countries adopted various safety measures, including masking, social distancing, and vaccination. However, there is a lack of methods that can quantitively evaluate the effectiveness of these countermeasures. To fill the gap, this research first develops a model to quantitively evaluate the infection risk of riding public transit. By utilizing the developed model, the effectiveness of different countermeasures could be evaluated and compared. For demonstration purposes, the developed model is applied to a particular bus route in the City of Houston, Texas. The modeling results show that masking, social distancing and vaccination can all reduce the infection risk for passengers. And among all these countermeasures, face masking is the most effective one. In addition, model results also prove that the COVID-19 infection risk is highly related to the exposure time and the risk can be controlled by reducing the exposure time. Thus, a new strategy named “split route strategy” is proposed and compared with the “capacity reduction strategy” using the model developed. In addition, a cost-benefit analysis is performed to assess the feasibility of the proposed “split route strategy”. Furthermore, two interviews were conducted with practitioners at Houston Metro. Both interviewees believe that face masking could significantly prevent the spread of the virus, which validated the model results. Finally, conclusions and recommendations are provided according to the findings of this research.

Chapter 1. Introduction

1.1 Problem Statement

COVID-19 has dramatically affected people's travel behaviors and the public transit service. Riding public transit is one of the major causes helping the spread of the virus as current evidence suggests that the virus spreads mainly between people who are in close contact with each other at a conversational distance, especially in poorly ventilated and/or crowded indoor settings (WTO, 2021). Previous studies have revealed that due to the COVID-19 pandemic, public transit has experienced a sharp ridership decline worldwide due to the shutdown of the country and stay-at-home orders (EBP, 2020). Recently, with the availability and accessibility of COVID-19 vaccines, more and more countries have reopened, and the demand for public transit started to bounce back. However, with the recent more infectious variant Omicron and its subvariants, the risk of getting infected remains high. According to Polzin (2021), Transportation planning after COVID-19 remains a great challenge for public transit agencies. During the pandemic, several countermeasures have been implemented by public transit agencies, including face masking, social distancing, and disinfecting. In addition, the development of COVID-19 vaccines also helps to keep passengers safe while riding public transit. The effectiveness of these countermeasures has been assessed by some previous studies (Pradhan et al., 2020; Roy et al., 2020; Eikenberry et al., 2020; Celina et al., 2020). However, there is a lack of research methods that can quantitively evaluate the effectiveness of these existing countermeasures.

In addition, some countermeasures are costly and consume a significant amount of resources. For example, during the pandemic, to keep social distance, most of the public transit agencies reduced vehicle capacity limitation from 25% to 75% to keep passengers at least 6 feet distance from each other. Due to the recovering transit demand, if we still use this countermeasure during the post-COVID-19 era, it will require more vehicles and more drivers and will significantly increase the operational cost of the transit agencies. For a long-term operation, we cannot afford capacity reduction and we need to find more cost-effective solutions that can meet the recovering public transit demand while minimizing the infection risk for passengers in the post-COVID-19 era. To assess the effectiveness and feasibility of these new solutions before implementation, a quantitative method is also required.

To address the problem, this study develops a method that can quantitively evaluate the infection risk of riding public transit. By using the developed method, the benefits of different countermeasures in terms of infection risk reduction can be assessed.

1.2 Objectives

This project aims to recommend cost-effective countermeasures for maintaining safe and effective public transit services during the post-COVID-19 and to develop a method for quantitively evaluating the effectiveness of these countermeasures.

1.3 Expected Contributions

The developed model could help public transit authorities evaluate the effectiveness of countermeasures to prevent the spread of the COVID-19 virus in public transit before implementing them. It can help public transit agencies choose the most cost-effective countermeasures and strategies and maintain high-quality public transit service.

1.4 Report Overview

The remainder of this report is organized as follows: In Chapter 2, current research on the countermeasures to prevent the spread of COVID-19 in confined spaces, especially in public transit was introduced, as well as the methods to assess the effectiveness of these countermeasures. After that, the process to develop the "modified Wells-Riley model" was introduced. For demonstration purposes, the developed model is applied to a particular bus route in the City of Houston, Texas. In addition, interviews with a lead planner and a bus driver at Houston Metro are conducted to get feedback from the practitioners. Finally, conclusions and recommendations are provided.

Chapter 2. Literature Review

Since the outbreak of COVID-19, many research works have been conducted to investigate the countermeasures for preventing the spread of the coronavirus. The most commonly used countermeasures are face masking, social distancing, disinfecting, and vaccination. Some of them have been investigated by previous studies. In this part, studies on countermeasures used by public transit agencies will be introduced first, followed by the research quantitively assessing the transmission risk in confined spaces with or without safety countermeasures.

2.1 Countermeasures

Pradhan et al. (2020) reviewed the potential interventions to prevent the spread of the COVID-19 virus, including surface disinfecting, hand sanitization, and wearing personal protective equipment (PPE), and pointed out that the effectiveness of these measures completely relies on the strength of disinfectants, hand sanitizer and the material of the PPE. Roy et al. (2020) also highlighted the role of surface disinfection and hand disinfection during the COVID-19 pandemic in their paper. The authors stated that since coronavirus can be easily inactivated by chemical disinfectants, it’s very important to correctly use disinfectants. Disinfection with appropriate and recommended disinfectants will not only reduce the spread of the disease but also play a significant part in flattening the curve.

Eikenberry et al. (2020) investigated and confirmed the effectiveness of the use of face masks to prevent the virus. Authors found that even relatively ineffective face masks can reduce the spread of COVID-19 and decrease hospitalizations and deaths. In addition, masks are not only useful for preventing illness in healthy people but also for preventing asymptomatic transmission.

Matrajt and Leung (2020) found that the new cases, hospitalizations, and deaths were reduced when social distancing interventions were taken place. However, if the social distancing ended, then the epidemic rebounded. Adeke et al. (2021) investigated the transmissibility of COVID-19 among passengers using public transport modes in the Makurdi metropolis, Nigeria, and revealed that public transport modes operated safely when carrying capacities below normal at 50% full.

Kamga and Eickemeyer (2021) comprehensively reviewed the literature to explore social distancing measures deployed by the public transportation industry in the United States and Canada during the COVID-19 pandemic. The authors concluded that social distancing is effective in containing the spread of diseases, such as influenza and COVID-19, especially when there are no effective vaccines and treatments. Social distancing is particularly important in places where community transmission is substantial.

Lucchesi et al. (2022) conducted an online survey with public transportation users in a metropolitan area in southern Brazil and identified the immediate countermeasures which can increase the users' perception of protection while riding public transport. These countermeasures include limiting the number of people in the vehicles, wearing masks, and vehicle hygiene. Tirachini and Cats (2020) recommended incorporating public health considerations into transportation service planning in the post-COVID-19 era, which include keeping physical distancing in public transportation, managing capacity, and crowding levels to reduce infection risk, and redesigning services. Kapatsila and Grise (2021) found that an individual is more likely to feel safe using public transit when better informed about the measures the transit agency is taking to ensure physical distancing. It is recommended that transit agencies continuously communicate with riders regarding ongoing efforts to promote the health and safety of all users.

S.G. Borjigin et al. (2023) assessed the effectiveness of various mitigation strategies to reduce the risk of COVID-19 transmission in transit buses using an agent-based simulation modeling (ABSM) approach. The authors used simulation software to simulate the movement of passengers and the transmission of COVID-19 in transit buses. The ABSM approach used in this study allowed the authors to simulate different scenarios with varying passenger loads, mask-wearing rates, and ventilation conditions. The authors found that reducing passenger capacity, wearing face masks, and opening half the windows for ventilation are effective strategies for reducing the risk of COVID-19 transmission in transit buses. They also found that the effectiveness of these strategies depends on the passenger load and the duration of the bus ride. The authors suggested that increasing the ventilation rate is an effective strategy for reducing the risk of COVID-19 transmission in transit buses, particularly in scenarios where the passenger load is high, and the duration of the bus ride is long. One limitation of this study is that it does not take into account the differences in the behavior and preferences of passengers. The authors assumed that all passengers wear masks and follow social distancing guidelines, which may not reflect the reality in some settings. Additionally, the study only considered the transmission of COVID-19 through airborne droplets and did not consider other modes of transmission, such as surface contamination.

2.2 Quantitative assessment of the effectiveness of the Countermeasures

Although the mechanism of COVID-19 is still under investigation, several studies have been conducted to assess the effectiveness of the safety countermeasures in public transit or other confined spaces. Different methods or mathematical models were developed by previous studies.

Chu et al. (2020) conducted a meta-analysis to investigate the optimum distance to avoid person-to-person virus transmission and to assess the effectiveness of face masks and eye protection. Key findings of this study include: 1) viruses transmission was lower with the physical distancing of 1 meter or more, compared with a distance of less than 1 meter; 2) face mask use could largely reduce the risk of infection; 3) eye protection was found to be associated with less infection. Worby and Chang (2020) studied the role of face masking in the general population to stop the spread of the virus using mathematical modeling. Their results show that face masking is an effective strategy for mitigating the transmission of COVID-19. In addition, the authors claimed that the use of face masks is more beneficial to people with higher contact rates, such as passengers, and recommended implementing it with other strategies.

Matrajt and Leung (2020) used a mathematical model to quantify the short-term effectiveness of social distancing to delay the curve of COVID-19 for different age groups. Four different social distancing intervention scenarios were designed by considering the population with different age distributions and different social contact distances. With the developed age-structured susceptible-exposed-infectious-removed model, the authors found that keeping social distance in all age groups significantly reduced the number of cases and flatten the curve of COVID-19 the best. Berg et al. (2021) further investigated the effectiveness of 3-foot social distancing versus 6- feet social distancing for mitigating the spread of COVID-19 among primary and secondary students and staff. Infection rate ratios for students and staff members were estimated using log-binomial regression. The authors found that student case rates and staff case rates were both similar for 3- feet and 6- feet social distancing, which indicated that social distancing could be less effective in school settings with mandatory masking. Kwon et al. (2020) conducted prospective analyses with data collected from 198,077 participants in the U.S. and discovered that good social distancing can reduce the infection risk of COVID-19 by 31% compared with people living in communities with poor social distancing. In addition, for individuals living in communities with poor social distancing, wearing face masks could reduce the risk of COVID-19 by 63% compared with people not wearing face masks. Ku et al. (2021) analyzed the impacts of mandatorily wearing masks and practicing social distancing in public transit during the COVID-19 outbreaks in South Korea. First, to examine the effectiveness of wearing masks, a cough aerosol simulator was used to measure the formation of cough aerosols and their blockage by a mask. Experimental results showed that most of the particles were blocked by the mask, and most of the particles that passed through the mask were smaller than 576nm. Next, it simulated how passengers encounter each other and get infected by tracking their movements. The probabilities of being exposed to an infected person with or without wearing face masks and practicing social distancing were then estimated and compared. The authors concluded that both wearing masks and practicing social distancing would reduce the number of exposed passengers in public transit greatly.

Vecherin et al. (2022) assessed the COVID-19 infection risk at a workplace with a stochastic model. The model was derived from microexposure modeling, agent-based modeling, and probabilistic modeling. The developed model could be used as a decision-making model for risk assessment at a workplace and it needs the information of the daily routines of each employee and the workplace setting. Edwards et al. (2021) also conducted a study that captured aerosol dispersion patterns from a mechanical exhalation simulation. This research quantified the effectiveness of using onboard fans, opening different windows, the use of face masks, and the use of the transit bus AC system considering turbulent air and any effects of momentum inside a moving bus. Results show that wearing face masks reduced the overall particle count released into the bus by an average of 50% or more depending on mask quality and reduced the dispersion distance by several feet. In addition, it was indicated that ventilation significantly reduces passengers' overall exposure time and concentration to potentially infectious aerosols on the bus. Note that, it is an experimental-based study and no analytical models have been developed in this study.

Several studies utilized or developed modified Wells-Riley models to assess the infection risk in public transit or other confined spaces. Sun and Zhai (2020) investigated the effectiveness of social distancing and ventilation in controlling COVID-19 transmission in confined spaces. The authors introduced the social distancing index and ventilation index into the Wells-Riley model. The model was validated with data collected from three real pandemic cases, including a bus outbreak in Hunan, China, a bus outbreak in Ningbo, China, and an airplane outbreak in Iran. With the validated model, the infection risks were projected for different scenarios, such as vehicles and building spaces. Their results showed that the infection risk could be reduced by increasing social distance or increasing the ventilation rate. Dai and Zhao (2020) estimated the infection rate of COVID-19 in a confined space considering the ventilation rate. To determine the quantum generation rate q of COVID-19, the authors first used the information of other similar airborne transmitted diseases to fit the curve and then estimated the q of COVID-19 based on the fitted equation. The model was applied to some typical scenarios, including offices, classrooms, buses, and aircraft cabins. In addition, the effectiveness of wearing a mask was also been evaluated. Results indicated that wearing an ordinary medical surgical mask in a confined space could significantly reduce the infection risk. Harrichandra et al. (2020) also assessed the COVID-19 transmission risk in New York City nail salons with the Wells-Raily equation. When not wearing masks, the risk of infection across all 12 selected salons and 5 exposure scenarios ranged from <0.015% to 99.25%, with an average risk of 24.77%. When wearing masks, the risk of infection ranged from <0.01% to 51.96%, with an average of 7.3%. The results show that increasing airflow rate and the use of face masks could reduce COVID-19 transmission in nail salons.

2.3 Survey and Review Papers

Liu et al. (2022) presented the main transmission mechanisms, forecasting, risks, and prevention mechanisms of the COVID-19 pandemic in public transportation through a disaster management lens, identifying techniques for modeling and understanding risks for mitigating and preventing them. Scientific literature was drawn from transportation research, epidemiology, medical sciences, environmental sciences, and computing. Different transportation modes were separated from each other and the study reflects on how the current scientific understanding relates to transmission risks and their management. Mediating factors such as ventilation, layout and seat arrangement, occupancy rate, duration of the trip, passenger density, cleaning, and hygiene were considered and how they affect transmission of this virus. Novel insights that can be used to help manage these risks in different public vehicles were derived and open challenges for the research community were identified by authors.

This paper also revealed that for transportation planning, it is necessary to understand the spread of COVID-19 between individuals. Various preventive measures such as total lockdown of public and private business centers, international travel bans, and other restrictions were among the earliest COVID-19 countermeasures for stemming the tide of the infections. Various forecasting models were devised to help policymakers, clinicians, and public health practitioners and as well help keep people safe during pandemic outbreaks. These models were affected by spatial, scale, population density, and data.

Olayode et al. (2022) reviewed 140 journals and conference articles using the inclusion and exclusion criteria methods. These articles were obtained from various academic databases such as Google Scholars, Scopus, and Web of Science using the keywords 'Public transportation', 'COVID-19 Pandemic', 'Physical distancing', and 'face masks'. The selection of these articles was narrowed down to 100 after applying the inclusion and exclusion criteria. This study examined the preventive measures recommended by the World Health Organization to reduce the spread of the COVID-19 pandemic ranging from physical distancing, use of face masks, and keeping physical hygiene.

This study reviewed the importance of physical distancing as one of the most non-pharmaceutical methods for preventing COVID-19 transmission. Keeping at least 1m from other people was recommended by the World Health Organization (WHO) to limit the risk of COVID-19 transmission in transportation systems for pedestrians and public transportation users (WHO, 2020). Studies also revealed that the use of face masks can considerably lower the quantity of infectious COVID-19 in exhaled breath, especially in asymptomatic ill persons (Prather et al., 2020; Leung et al., 2020; Han et al., 2020). These masks must be logically fitted and handled which makes it an effective strategy to prevent the transmission of the COVID-19 pandemic.

Moreover, COVID-19 has posed serious socio-economic threats globally. Governments and businesses have experienced severe economic downturns. In the early days of the COVID-19 pandemic, the spread of this virus becomes the largest socio-economic crisis globally. According to (Valentino et al., 2020; Tanguay et al., 2020; Astroza et al., 2020), there was a drastic decline in the use of public transportation systems. People working in jobs with higher salaries have access to work remotely in countries like the U.S., Canada, and Chile. Recent surveys reported that high school certificate workers and females were mostly affected by the pandemic in the job market (Adams-Prassl et al., 2020).

This paper devised some measures to reduce the effects of the COVID-19 pandemic on public transportation systems such as integrating public health into service planning, introducing social distancing policy into public transportation systems, and as well evaluating the resilience of public transportation systems and their capability. The study also suggested that there should be a periodic evaluation of the rate of spread of COVID-19 in public transportation. It was further recommended that research should be made to evaluate the effects of the COVID-19 pandemic on the traffic flow of vehicles, bicycles, and motorbikes before, during, and after the pandemic which focuses on road intersections and freeways.

The COVID-19 pandemic has led to significant changes in daily life, including the implementation of various safety measures in public transit spaces to reduce the risk of virus transmission. In this study, Navarrete-Hernandez et al. (2023) evaluated the impact of these safety measures on riders' worry about virus contraction in public transit spaces. The authors surveyed transit riders in three different cities namely London, Milan, and Santiago to assess their level of worry about contracting COVID-19 while using public transit before and after the implementation of various safety measures. The safety measures included in the study were mask mandates, social distancing guidelines, and the wearing of face masks. The survey data was analyzed using statistical methods to determine the impact of these measures on riders' worry about virus contraction.

The results of the study showed that the implementation of safety measures in public transit spaces had a significant impact on riders' worry about virus contraction. Specifically, the authors found that mask mandates and social distancing were the most effective measures in reducing riders' worry about virus contraction. Hand sanitization was also found to have a positive impact on riders' worry, although to a lesser extent. The study also found that the worry of virus contraction was significantly associated with several factors, including age, gender, income, and education level. In addition, the study found that participants who perceived the COVID-19 safety measures as effective reported lower levels of worry about virus contraction.

This study is significant because it sheds light on the effectiveness of safety measures implemented in public transit spaces and their impact on riders' worry about contracting the virus. However, there are a few limitations to the study. The study did not consider people with compromised immune systems who are the most vulnerable to COVID-19 infection.

2.4 Summary

From the literature review, it can be seen that most of the existing studies only compared the effectiveness of 1 or 2 types of countermeasures under different conditions, such as different population groups, different social distance levels, and different communities. There is a lack of methods that can quantitatively estimate the infection risk of different countermeasures under different conditions. Also, no existing studies have considered the effects of vaccination on infection risk. This study is to fill these gaps.

Chapter 3. Model Development

3.1 Wells-Riley model

To assess the effectiveness of various countermeasures, in this research, a “modified Wells-Riley model” is developed to evaluate the association between the infection probability and the ventilation rate, social distancing, masking, and vaccination.

The Wells-Riley model is one of the most classic models for predicting the infection risk for airborne transmission diseases. It was developed by William F. Wells and Richard L. Riley for tuberculosis and measles (Riley et al., 1978 and Riley, 2001), but has been widely used for other diseases transmitted in the air. Although it is very simple, the Wells-Riley model can predict the infection probability in a confined space with variables under control, such as room ventilation rate. Therefore, it was chosen to measure the infection risk of COVID-19 in public transit spaces.

The Wells-Riley model can be mathematically expressed by the following Equation (Riley et al., 1978).

$$P = \frac{C}{S} = 1 - e^{-Iqpt/Q} \quad (1)$$

Where,

P is the probability of infection risk;

C is the number of cases that develop infection;

S is the number of susceptible people;

I is the number of source patients (infectors);

q is the quantum generation rate produced by one infector (quantum/h);

p is the pulmonary ventilation rate of each susceptible individual (m3/h);

t is the exposure time (h);

Q is the room ventilation rate (m3/h).

3.2 Modified Wells-Riley model by Sun and Zhai (2020)

In the original Wells-Riley model, room ventilation rate Q is the only factor considered. To consider the impacts of social distance and ventilation effectiveness on the infection risk, Sun and Zhai (2020) have modified the Wells-Riley model. For a confined space, different ventilation systems can cause different air distribution patterns and therefore affect ventilation efficiency. In addition, social distancing has been identified as an important countermeasure for preventing the spread of coronavirus. During the pandemic, public transit agencies reduced vehicle capacity from 25% to 75% to keep passengers at least 6 feet distance (Qi et al., 2021). In Sun and Zhai (2020), a relationship between the statistical probability of droplets in different sizes and their transmission distances was built by curve fitting. A social distance index Pd was developed. Basically, Pd increases with the decrease of transmission distance and it could be expressed as a function of distance d(m) as follows:

$$P_d = (-18.19\ln(d) + 43.276)/100 \quad (2)$$

Then, to consider the effects of ventilation effectiveness, an air distribution effectiveness factor (Ez) was incorporated into the model, and the Wells-Riley model was modified as

$$P = \frac{C}{S} = 1 - e^{\frac{(-Bqpt)P_d}{Ez(\frac{Q}{N})}} \quad (3)$$

Where,

Pd is the social distance index (see Equation 2);

B is the infection rate (the percentage of infectors) ;

Ez is the air distribution effectiveness;

N is the total number of passengers/occupants.

In Sun and Zhai (2020), the social distances for some typical public transportation scenarios were provided. Then, according to Equation (2), the Pds (social distance index) for these scenarios were calculated and listed in Table 1. In addition, the ventilation rate (Q) and air distribution effectiveness (Ez) for some typical public transportation scenarios were also summarized in Table 1.

Table 3-1 Air Distribution Effectiveness and Social Distance Index for Some Typical Public Transportation Scenarios

Scenario	Length (m)	Width (m)	Social distance, d(m)	Distance index with 100% occupancy ($P_d^{100\%}$)	Distance index with 50% occupancy ($P_d^{50\%}$)	Distance index with 25% occupancy ($P_d^{25\%}$)	Ventilation rate with clear air, Q/N(m^3/hp)	Air distribution effectiveness (*Ez*)
Long bus	13.7	2.55	0.72	49.3%	36.7%	24.0%	20	1
Air cabin	-	-	0.78	48%	35.2%	22.5%	25	1
Subway	22	3	0.57	53.4%	40.8%	28.3%	20	0.8
High-speed train	25	3.3	0.99	43.5%	30.9%	18.2%	20	1

**Adopted from Sun and Zhai (2020)*

Besides social distancing, face masking and vaccination are also considered the countermeasures for preventing the spread of the coronavirus, which could also affect the infection risk for passengers. To assess the effectiveness of these countermeasures, the following adjustment factors were developed to further modify the Wells-Riley model:

- The adjustment factors for face masking
- The adjustment factors for vaccination

The adjustment factors for face masking

At the beginning of the pandemic, to stop the spread of the coronavirus, face masking is required at all public transit. For infected persons, wearing a mask can dilute the concentration of pathogens exhaled, and for susceptible persons, wearing a mask can dilute the concentration of pathogens inhaled. To justify the effect of face masking, Dai and Zhao (2020) proposed to add two adjustment factors η_1 and η_2 to the Wells-Riley equation as follows:

$$P = \frac{C}{S} = 1 - e^{\frac{(-Bqpt)(1-\eta 1)(1-\eta 2)P_d}{Ez(\frac{Q}{N})}} \tag{4}$$

Where,

η_1 is the exhalation filtration efficiency
η_2 is the inhalation respiration filtration efficiency

In their study, if the face mask is worn, η_1 and η_2 were set to be 0.5 considering that the filtration efficiency of ordinary medical-surgical masks for virus-carrying aerosols is about 60% (Hui et al. 2012), and the existence of air leakage (Davies et al. 2013). η_1 and η_2 were set to 0 if the face mask is not worn.

The adjustment factors for vaccination

To halt the rapid spread of the coronavirus, countries started to launch national COVID-19 vaccination campaigns. Several clinical trials have proved the effectiveness of vaccines to protect people against COVID-19. Currently, the vaccines are widely available in the US and 59.7% of the population have been fully vaccinated by the end of November 2021 (Mayo Clinic, 2021). This is a local-specific factor because the vaccination rates in different areas are different. For example, in Texas, about 54.7 % of the population is fully vaccinated by the end of November 2021, which is lower than the national average. Therefore, when considering the impacts of vaccination on the risk of riding public transit, both vaccine effectiveness and the vaccination rate should be considered. Thus, two vaccination-related adjustment factors, the effectiveness of the vaccine *(Ev)* and the vaccination rate (γ) are also added to the model. In addition, since people are considered fully vaccinated two weeks after getting the second dose, the vaccination rate considered here should be the full vaccination rate. Finally, the modified Wells-Riley model can be expressed by Equation (5) when considering social distance, face masking, and vaccination:

$$P = \frac{C}{S} = \left(1 - e^{\frac{(-Bqpt)(1-\eta 1)(1-\eta 2)P_d}{Ez(\frac{Q}{N})}}\right)(1 - \gamma * Ev) \tag{5}$$

Where,

Ev is the effectiveness of the vaccine;
γ is the vaccination rate;

Note that, the previous versions of the Wells-Riley model cannot assess the effects of vaccination on infection risk. The proposed modified Wells-Riley model filled this gap.

Determine the parameters of the modified Wells-Riley model

In this study, the values of the model parameters were selected either based on our literature review or reasonable assumptions. The suggested values of the model parameters selection are listed in the following Table 2. Among these parameters, the vaccination rate (γ) and infection rate (*B)* are local-specific factors and their values need to be determined according to the vaccination rate and infection rate of the study area. In this study, the infection rate was calculated by using the following equation:

$$B = \frac{Total\ \#\ of\ comfirmed\ COVID\ cases\ \ during\ the\ past\ 10\ days}{Population} * 100\% \tag{6}$$

Note that, in Equation (6), we used the total number of confirmed COVID cases during the past 10 days because a person with COVID-19 is likely no longer contagious 10 days after testing positive for coronavirus (McCallum, 2021 and CDC, 2021).

The effectiveness of the vaccine *Ev* is assumed to be 35%. It is a conservative assumption according to the results of a recent study that considers the Omicron variant (Collins, 2021).

Table 3-2 Values of the Model Parameters

parameter	Notation	value	Reference	Note
q	quantum generation rate produced by one infector	48 quantum/h	Dai & Zhao, 2020	
$\eta_1=\eta_2$	η_1 is the exhalation filtration efficiency, and η_2 is the inhalation respiration filtration efficiency	0.5	Dai & Zhao, 2020	
p	pulmonary ventilation rate of each susceptible individual	0.3 m^3/h	Duan, Zhao & Wang, 2013	p=0.3 m^3/h when people sits or conduct light indoor activities
Q/N	room ventilation rate	Table 1	Sun & Zhai, 2020	
P_d	social distance index	Table 1	Sun & Zhai, 2020	For long bus
E_z	distribution effectiveness	Table 1	ASHRAE, 2019	Ceiling supply, floor return
E_v	Effectiveness of the vaccine	35%	Collins, 2021	Current estimation based on the vaccinations and the variants
γ	vaccination rate	local specific data		Based on the local fully vaccinated rate (%) (people received their final dose two weeks ago)
B	Infection rate	local specific data		Based on the local confirmed COVID cases and population (See Equation 6)

Chapter 4. Model Demonstration – Case Study

To demonstrate the application of the proposed modified Wells-Riley model, a case study is conducted to estimate the infection risk of COVID-19 on a particular bus route in the City of Houston, Texas. At first, the scenario design is introduced. Next, the modified Wells-Riley model is applied to estimate the infection risks of different scenarios.

4.1 Scenario Design

Houston local bus route 4 was selected to conduct the case study. Bus 4 has 120 stops departing from Mission Bend Transit Center and ending in Eastwood Transit Center as shown in Figure 1. Bus 4 operates every 10 minutes during peak hours (6:00 am – 9:00 am and 4:00 pm – 7:00 pm) and every 15 minutes during non-peak hours. The regular hours are from 4:51 am to 12:51 am every weekday, and the whole trip is 1.5 hours one-way.

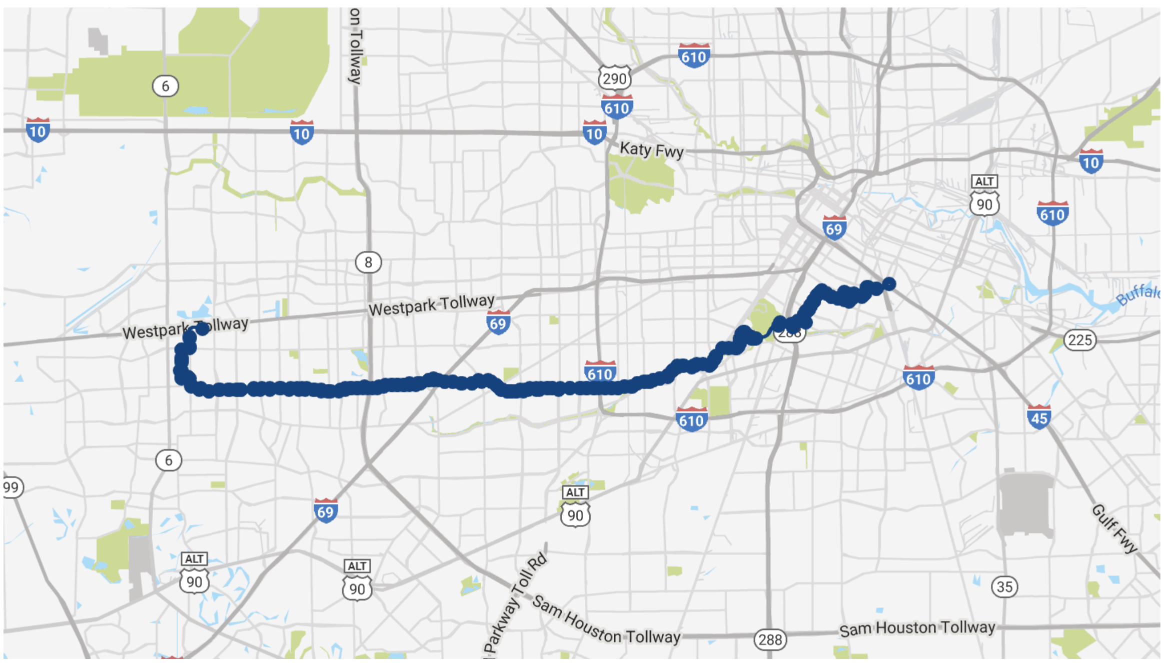

Figure 4-1 Bus 4 Routes in Houston, Taxes

Metro Houston currently has 1236 active buses, with the majority of them being 40-foot with about 40 seats. According to the Metro Ridership Report (2020), the average boardings for bus route 4 was about 7,872 on weekdays, 4,872 on Saturdays, and 4,180 on Sundays in January 2020, which was before the COVID-19 pandemic. The ridership decreased by about 50% during the pandemic and started to recover with the reopening of the State.

To estimate the infection risk of riding bus route 4 under different situations, the three most commonly used countermeasures are considered, which are: 1) face masking or not (M or NM), 2) different levels of social distancing (100% capacity, 50% capacity or 25% capacity), and 3) fully vaccinated or not (V or NV). Therefore, in total, the following 12 scenarios were designed.

1. 100% capacity, no masking, no vaccination (100%, NM,NV)
2. 100% capacity, masking, no vaccination (100%, M,NV)
3. 100% capacity, no masking, vaccination with current vaccination rate (100%, NM,V)
4. 100% capacity, masking, and vaccination with current vaccination rate (100%, M,V)
5. 50% capacity, no masking, no vaccination (50%, NM,NV)
6. 50% capacity, masking, no vaccination (50%, M,NV)
7. 50% capacity, no masking, vaccination with current vaccination rate (50%, NM,V)
8. 50% capacity, masking, and vaccination with current vaccination rate (50%, M,V)
9. 25% capacity, no masking, no vaccination (25%, NM,NV)
10. 25% capacity, masking, no vaccination (25%, M,NV)
11. 25% capacity, no masking, vaccination with current vaccination rate (25%, NM, V)
12. 25% capacity, masking, vaccination with current vaccination rate (25%, M,V)

4.2 **Calculate Infection Risk for The Designed Scenarios**

The infection risk of riding bus route 4 for different scenarios can be calculated by using the modified Wells-Riley model given in Equation (5). Most of the model parameters are provided in Table 2 except the two local-specific factors, i.e. the vaccination rate (γ) and infection rate (*B)*. According to Harris County COVID-19 Data Hub, 58% of the population in Houston will be fully vaccinated by the end of November 2021. Therefore, the vaccination rate (γ) is set to equal 58%. In addition, to calculate the infection rate, the highest number of confirmed cases in history for 10 consecutive days is used and the estimated infection rate (B) is 0.51%. Then, by inputting all estimated parameters to the modified Wells-Riley model given in Equation (5), the infection risk of riding bus route 4 for all 12 scenarios can be calculated. For example, for scenario 4 (100% capacity, masking, and vaccination with current vaccination rate), the infection risk of riding bus route 4 can be estimated by the following equation:

Scenario 4: 100% capacity, masking, and vaccination with current vaccination rate (100%, M, V)

$$P^{100\%, M, V} = \frac{C}{S} = \left(1 - e^{\frac{(-0.51*48*03*t)(1-0.5\ )(1-0.5\ )49.3\%}{20*1}}\right) * \ (1 - 58\% * 35\%) \qquad (7)$$

$$=0.203(1-e^{-0.045t})$$

4.3 Results and Discussions

The estimated infection possibilities (P) for all the scenarios are presented in Figure 2. It shows the relationship between infection possibility (P) with the exposure time (t). It can be seen that for all 12 scenarios, the infection risk increases rapidly with the increase in exposure time. When the other two factors (masking or not and vaccinating or not) are controlled, the risk of infection is highest when the bus capacity is 100%. As the bus capacity reduces to 50% and 25%, the social distance increases and the risk of infection decreases.

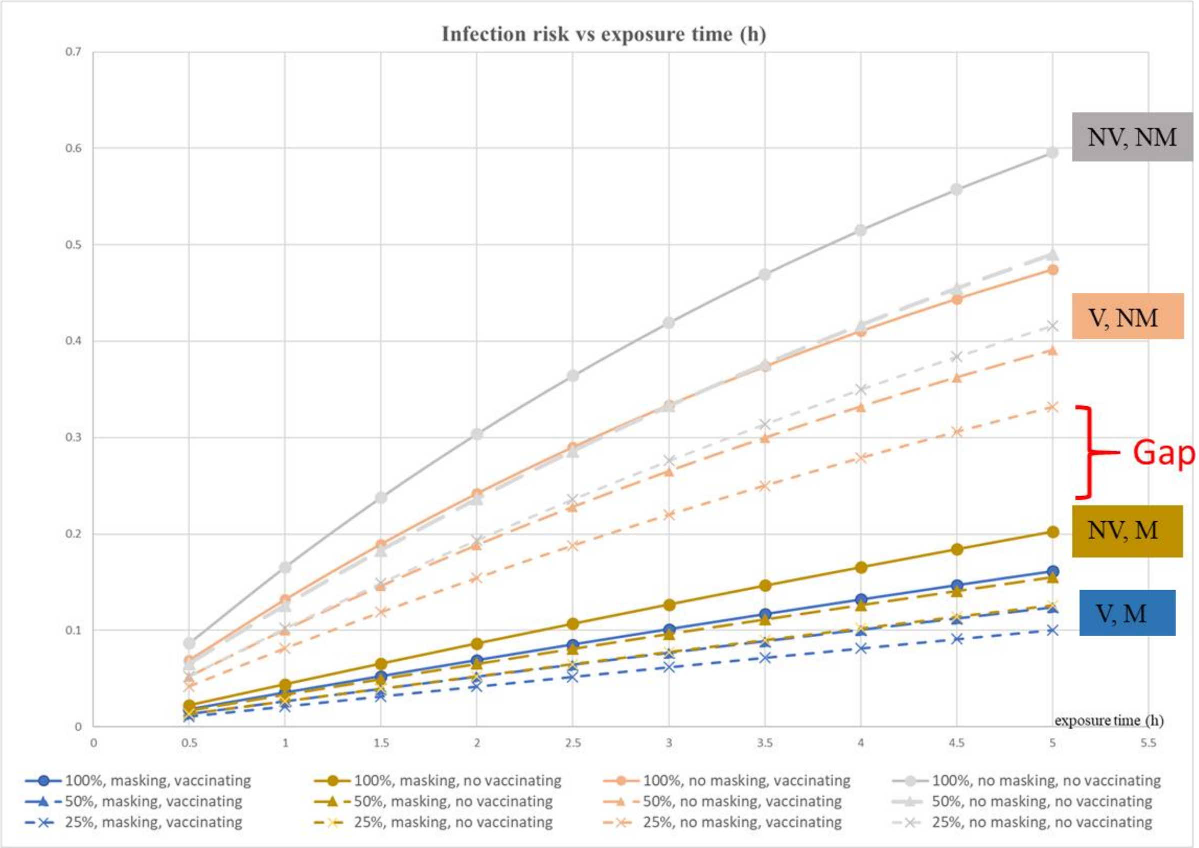

Figure 4-2 Infection Risk vs Exposure Time for Different Scenarios

Masking and vaccination also reduce the infection risk for passengers. When passengers all wearing masks and were vaccinated, the infection risk was reduced to the lowest. The results prove that masking, social distancing, and vaccination, do reduce the infection risk for passengers. It was also found that the lines for the scenarios of vaccination but no masking (V, NM) are above the lines for the scenarios of no vaccination but masking (NV, M), which indicates that masking is more effective in reducing infection risk than vaccination. In addition, there is a big gap between the lines for the scenarios of no masking and the lines for the scenarios of masking), which indicates that masking can significantly reduce the infection risk. The result supports the CDC's recommendation that people need to mask up in public indoor places regardless of vaccination status.

Chapter 5. Interviews with Transportation Practitioners

To add the practical value of this research, as well as to validate the model results, two interviews with practitioners at the Metropolitan Transit Authority of Harris County (Houston Metro) were conducted. The interview questionnaire contains four parts which are the interviewee's basic information, changes in transit operation during and post the pandemic, safety countermeasures and their effectiveness, and their opinions on the new strategy proposed by this research.

In this study, a lead transit planner and a bus operator at Houston Metro were invited for the interviews so the perspectives of both planner and frontline bus operator were gathered. Both interviews lasted around 40 minutes. The major findings from the interviews are summarized as follows:

1) The ridership of Houston Metro reduced sharply at the beginning of the pandemic, however, it has gradually recovered and certain stations started to get congested now.
2) Houston Metro already took all the precautions to protect passengers and drivers, such as a mask mandate, providing masks and hand sanitizers on the buses and at the bus stations, and disinfecting buses and facilities at bus stations.
3) Both interviewees believe face masking is the best countermeasure to prevent the spread of COVID-19 in buses.
4) Although the mask mandate remains effective, there's a large number of passengers do not comply with the policy. Some passengers refused to put on a mask even were offered one by the bus operator, and some passengers took off masks after being seated. Since the priority and responsibility of a bus operator are to safely transport the passengers from origin to destination, no further action was taken for passengers refusing to put on the mask.
5) Compared to before, the buses get disinfected more frequently since the pandemic. According to the information provided by interviewees, besides the daily disinfection, currently, all buses entering a transit center will get thoroughly disinfected.
6) Although there is a statistic about the total number of infected metro staff, it can not tell the source of the infection. There is no statistic about the number of passengers who got infected from riding public transit since there is no contact tracing of passengers.
7) The new strategy proposed by this study was also discussed during the interview. It will be introduced in detail in the next section.

Chapter 6. Propose a New Strategy and Evaluate Its Effectiveness

6.1 "Split Route Strategy"

These results of the case study prove the effectiveness of face masking, social distancing, and vaccination. However, with the reopening of the country, face masking and social distancing are not required. In addition, upgrading the ventilation system also costs a lot to the transit agencies. Therefore, more cost-effective approaches that can reduce the infection risk are needed. According to the modeling results presented in Figure 2, it can be seen that the infection risk is highly correlated to the exposure time. The shorter the time passengers exposures to the virus in a confined public space, the less likely they will be infected by COVID-19. Therefore, we can control the infection risk by reducing the exposure time. According to this idea, a new strategy is proposed which is to cut the long route into short routes, and passengers will be transferred to a disinfected bus in an existing station in the middle of their trips. In this way, the exposure time of passengers will be reduced and it will not reduce the bus capacity. Therefore, it could keep passengers safe while meeting the increasing demands for public transit. The new strategy is referred to as the "split route strategy" in this study.

6.2 Effectiveness of the Proposed Strategy

To evaluate the effectiveness of the proposed strategy, the same bus route that we selected in the case study was used to demonstrate the implementation of such a strategy. Since face masking is not required but encouraged during the post-COVID-19, we assume that 50% of the passengers still wear masks. Also, we assume the vaccination rate can reach 70% in the post-COVID-19 era. Then, the infection risks for different capacities can be calculated as:

$$P^{100\%,70\%,V} = 50\% * P^{100\%,\ M,\ 70\%,\ V} + 50\% * P^{100\%,\ NM,70\%V}$$

$$P^{50\%,70\%,V} = 50\% * P^{50\%,\ M,\ 70\%,V} + 50\% * P^{50\%,\ NM,70\%V} \quad (8)$$

$$P^{25\%,70\%,\ V} = 50\% * P^{25\%,\ M,\ 70\%,V} + 50\% * P^{25\%,\ NM,\ 70\%V}$$

The estimated infection risks were presented in Figure 4. Since the whole trip is 1.5 hours, it can be seen from Figure 3 that the possibility of a passenger getting infected by COVID-19 is around 12% if the bus running at full capacity. If the bus is running at 50% capacity, the possibility of a passenger getting infected by COVID-19 is around 9%. If the bus is running at 25% capacity, then the possibility of a passenger getting infected is reduced to 7%.

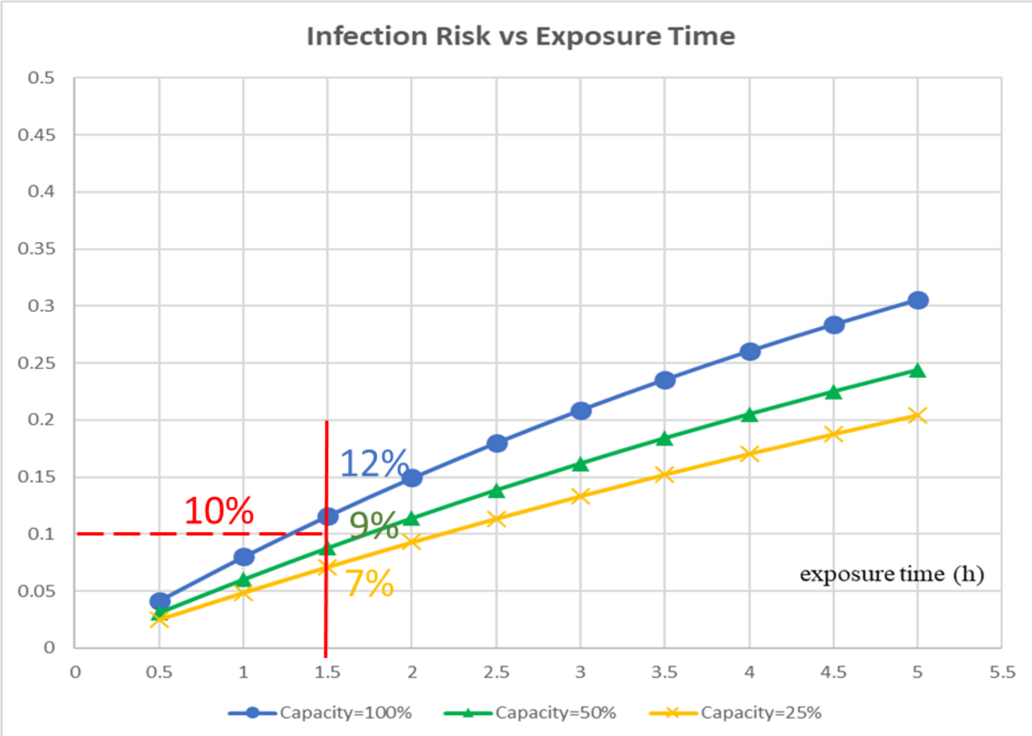

Figure 6-1. Infection Risk vs Exposure Time with 70% Vaccinating and 50% Masking Rates

Without reducing bus capacity, to keep the infection risk below 10%, the exposure time needs to be reduced. Since the whole trip is 1.5 hours, if we split this route into two parts, and ask passengers to transfer to another disinfected bus in the middle of the trip, then the infection risk would be controlled under 10%.

If without splitting the trip into two parts, another way to control the infection risk is to reduce the capacity. From Figure 3, we can see that to keep the infection risk under 10%, the capacity has to be reduced to 50%. Next, a cost-benefit analysis will be conducted to compare these two strategies: 1) the 50% capacity reduction strategy, and 2) the proposed route split strategy. For comparison purposes, a typical weekday in 2019 (before the COVID-19 outbreak) was selected to calculate the operational cost and revenue of bus Route 4.

Benefit Estimation

For Route 4, the average boardings on a weekday in 2019 are 8,067, so one typical weekday revenue from tickets is:

$1.25*8,067=$10, 083.75/day (9)

Cost Estimation

Current operational cost

According to Metro's schedule, Bus Route 4 provides frequent service every 10 minutes during peak times and 15 minutes during off-peak hours. For each direction, currently, there are 84 shifts on weekdays, 30 of which are during peak hours. In addition, the buses operate 20 hours per day, from 4:51 am to 12:51 am, and the oneway trip duration is 1.5 hours. Therefore, 30 buses are needed during peak hours and 20 buses are needed during non-peak hours for both directing on weekdays.

The median salary for a Metro bus driver is $16.71 per hour in Houston, the salary for cleaning staff is $12.13 per hour and the median average cost for a bus is $4.4 per hour calculated according to Federal Transit Administration's report (FTA, 2007). We assume cleaning staff are assigned to clean the bus at both terminals. The disinfecting supplier cost is $0.26 per gallon. It is also assumed one bus is around 1,600 square feet and the application rate per gallon of the solution is 250 square feet, therefore, it costs about $1.66 of the disinfecting supplier to disinfect a bus (Vitale, 2020). Therefore, the daily cost to operate this bus line is:

30 buses*($16.71+$4.4)/bus/hour*6 hours+20 buses*($16.71+$4.4)/bus/hour*14 hours + $12.13/hour/terminal*20 hours*2 terminals+$1.66/bus*(30 buses/hour*6 hours+20 buses/hour*14 hours)= $ 10,958.8/day (10)

Additional cost for the capacity reduction strategy

If not implementing the proposed strategy, to minimize the infection risk, buses should be operated at 50 % capacity. The original schedule may work during off-peak hours, but not during peak hours. To meet the travel demand during the peak hours, an additional 30 more buses should be added during the peak hour if the bus running at 50% capacity. Note that, the one-way trip is 1.5 hours and the round trip is 3 hours. Therefore, 30 more buses and bus drivers are needed for 3 hours during both morning and afternoon peak times (6 hours). The associated costs include bus operation costs and salaries for bus drivers, extra costs for cleaning staff (6 more hours needed for each terminal), and disinfecting supplier, which can be estimated as follows

($16.71+$4.4)/hour/bus * 6 hours*30 bus + $12.13/hour/terminal*6 hours*2 terminals+$1.66/bus*(30 buses/hour*6 hours) = $4,244.16/day (11)

Thus, the total cost for implementing a capacity reduction strategy will be:

$10,958.8/day + $4,244.16/day= $15,202.96/day (12)

Compared with the daily revenue calculated in Equation (9), it can be seen that the total cost of this strategy is much higher than the daily revenue. Thus, it is not feasible for transit agencies to implement such a strategy in the long run.

Additional operational cost for the proposed route split strategy

For the proposed split route strategy, the bus operates at full capacity, and passengers change to another disinfected bus in an existing station in the middle of the trip. Considering the full cycle of the bus route, two stations will be selected (one for each direction).   Assuming one cleaning staff are needed to quickly disinfect the bus, the increased costs would include the operation cost for two additional buses and two cleaning staff. The reason for only adding the cost of two buses is that the disinfected bus can be used by the next bus and there is only one bus that will stop at each selected bus station for disinfection. In the Houston area, the salary for cleaning staff is $12.13 per hour per person and the average cost for operating a bus is $4.4 per hour calculated according to FTA's estimation. In addition, more disinfecting suppliers are needed. Then, the total additional cost per weekday for the proposed route split strategy will be:

$12.13/hour/person*20 hours*2 person +$4.4/hour/bus *20 hours*2 bus + +$1.66/bus*(30 buses/hour*6 hours+20 buses/hour*14 hours) = $1,424.8/day (13)

Thus, the total cost for implementing the proposed strategy will be:

$10,958.8/day + $1,424.8/day= $12,383.6 /day (14)

By comparing with the daily revenue calculated in Equation (9), it can be seen that the total cost of this route split strategy is still higher than the daily revenue. However, it is much lower than the cost of the capacity reduction strategy. Thus, it may still be feasible for public transit agencies that have some other funding sources in addition to the ticket revenue.

Feedback from the practitioners

During the interview with the lead transit planner and bus operator at Houston Metro, the feasibility of the proposed "split route strategy" was also discussed. Both interviewees believe it is a good idea, and possibly reduces the infection risk for passengers, especially for those who need to take a long bus ride. However, there are a few obstacles to implementing this strategy now. The first problem is the lack of manpower. Hiring more drivers or cleaning staff requires more funding and transit agencies have very limited sources of funding. Second, asking all passengers to change buses in the middle of their trip will cause extra delays and interrupt the normal bus operation. Finally, this strategy may not be well accepted by some passengers.

Note that, we propose this new strategy as mainly for demonstrating the application of the developed model for assessing the feasibility of different strategies. This new strategy has some disadvantages as pointed out by the two interviewees. Thus, the transit agencies need to carefully evaluate all the aspects when making their decisions on implementing this strategy.

Chapter 7. Conclusions and Recommendations

In this paper, a modified Wells-Riley model was developed for estimating the COVID-19 infection risk of riding public transit by considering the impacts of different factors, including social distancing, wearing masks, and vaccination. By using the developed model, the effectiveness of different countermeasures for preventing COVID-19 spread can be quantitatively assessed.

7.1 Key Findings

To demonstrate the application of the proposed modified Wells-Riley model, a case study is conducted to estimate the infection risk of COVID-19 on a particular bus route in the City of Houston, Texas. To add the practical value of this research, interviews with a lead transit planner and a bus operator at Houston Metro were also conducted. Following are some key findings:

- Model results show that face masking, social distancing, and vaccination can all reduce the infection risk for passengers, and both interviewees agreed with this conclusion.
- Model results indicate that COVID-19 infection risk is highly correlated to the exposure time and the infection risk can be controlled by reducing the exposure time.
- Model results prove that face masking can significantly reduce the infection risk and is more effective than the current vaccination. Both interviewees also highlighted the importance of wearing masks on buses.

7.2 Policy Implications

First, since face masking can significantly reduce the infection risk, many states and transportation agencies issued mask mandates. For example, Washington, D.C., and Puerto Rico require people over age 2 to wear face masks in indoor public places regardless of vaccination status. Five states (AZ, CT, DE, KY, NJ) have made requirements for all people over age 2 to wear masks in public transit (AARP, 2021). CDC does not require wearing a mask in outdoor areas of transportation conveyances, however, while in indoor areas of conveyances or while indoors at transportation hubs, people are required to wear a mask except under certain circumstances (CDC, 2021). In addition, FTA extended the face mask requirement for all transportation networks, including public transportation through March 18, 2022 (FTA, 2021). The results of this research also prove the effectiveness of wearing face masks in reducing infection risks. Therefore, it is highly recommended that face masks should be required when riding public transit, especially in areas with a high number of COVID-19 cases. In addition, the interviewed bus operator pointed out that there’s still a compliance issue with the current mask mandate. Some passengers refused to wear masks and even they were offered a new mask by the operators, and some passengers took off their masks after being seated and couldn’t wear masks throughout their whole trips. Therefore, more public education or campaigns are needed to raise awareness of the importance of wearing masks. Our results provide good support for such efforts.

Second, since COVID-19 infection risk is highly correlated to exposure time, more strategies aimed at reducing the exposure time should be considered. For example, in this study, a “split route” strategy was proposed. The effectiveness of this proposed strategy was estimated by using the developed model and a cost-benefit analysis was conducted. The result shows that the proposed strategy can control the COVID-19 infection risk and has a much lower cost compared with the capacity reduction strategy that has been widely used by the transit agency during the pandemic. Besides, other strategies, such as providing express service to passengers who need to take a long ride to reduce their exposure time can also be considered.

Finally, since the developed model considers various factors that affect the infection risk, including social distance, ventilation rate, air distribution effectiveness, masking, vaccination, and exposure time, it can be used for assessing the effectiveness of different countermeasures and operational strategies that aim at reducing the COVID-19 infection risk of riding public transit. Thus, it will help public transit agencies maintain safe and effective public transit services during the post-COVID-19 era.

7.3 Limitations and Future Study Needs

Although the proposed model considers more countermeasures than other research, there are still some limitations.

First, this study focuses on the countermeasures related to social distance, face masking, vaccination, and exposure time. In the future, more countermeasures related to ventilation rate and air distribution effectiveness also need to be investigated and their effectiveness needs to be assessed using the proposed model.

Second, because there is no contact tracing of passengers who got infected while riding public transit, necessary data is not available to validate the proposed model. In the future, a large-scale transit rider survey needs to be conducted to derive some risk indexes of using different public transit services in different areas to validate the model results. In this study, due to time and funding constraints, we only conducted interviews with a lead transit planner and a bus operator at Houston Metro. Our model results were supported by the interview results, which could validate the model to a certain extent.

Third, the cost-benefit analysis in this study did not consider the cost of travel time for the proposed “split route” and “capacity reduction “strategies. The transfer of the bus will cause an additional 5-10 minutes of delay to the passengers. However, there is no data available on the number of passengers affected by this strategy and the need to change buses, so it is impossible to calculate the value of the delay. In addition, since it does not affect the operational cost of the transit, the cost of this additional travel delay is not included in our cost-benefit analysis. However, public transportation agencies should be aware of this cost when choosing bus routes and stations to implement this strategy. In the future, other costs, including social costs and traveler costs also need to be considered for a more comprehensive cost-benefit analysis.

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