論文 / 著書情報
Article / Book Information

題目(和文)	メタポピュレーションモデルを用いた交通政策介入によるパンデミック管理対策
Title(English)	Pandemic Control Measures Considering Transportation Interventions in Metapopulation Structure
著者(和文)	LiuYang
Author(English)	Yang Liu
出典(和文)	学位:博士(学術), 学位授与機関:東京科学大学, 報告番号:甲第390号, 授与年月日:2025年3月26日, 学位の種別:課程博士, 審査員:花岡 伸也,山下 幸彦,秋田 大輔,室町 泰徳,髙山 雄貴,杉下 佳辰
Citation(English)	Degree:Doctor (Academic), Conferring organization: Institute of Science Tokyo, Report number:甲第390号, Conferred date:2025/3/26, Degree Type:Course doctor, Examiner:,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

Thesis outline

The COVID-19 pandemic has profoundly disrupted global systems, exposing vulnerabilities in public health, transportation networks, and economic resilience. Governments worldwide faced the daunting challenge of balancing pandemic control measures with economic sustainability, revealing the critical need for an integrated approach that combines transportation interventions and vaccination strategies. Mobility restrictions, while effective in mitigating disease transmission, severely disrupted economic activities, underscoring the necessity for optimized pandemic control policies. Simultaneously, vaccines emerged as a crucial tool in pandemic mitigation, yet their uneven distribution across regions led to significant disparities in recovery rates. This study aims to address these challenges by developing a comprehensive optimization framework that integrates epidemiological dynamics, transportation restrictions, and vaccination strategies within a metapopulation structure. By accounting for spatial heterogeneities in population movement and infection risks, this research provides policymakers with data-driven insights to balance public health objectives with economic recovery. Additionally, the study explores the role of international cooperation, particularly through vaccine-sharing mechanisms, to enhance pandemic control and minimize socioeconomic impacts globally.

The research is structured into three main components, each addressing a distinct aspect of pandemic control. The first component focuses on the role of transportation control, specifically through the implementation of travel bubbles. International travel restrictions were among the most widely used non-pharmaceutical interventions (NPIs) during the early stages of the pandemic, when vaccines were not yet available. However, prolonged border closures had severe economic consequences, particularly for tourism-dependent nations. To address this challenge, the concept of travel bubbles was proposed as an intermediate strategy for gradually reopening borders while maintaining infection control. A travel bubble is a controlled travel corridor between regions with low infection rates, allowing restricted but stable mobility to sustain economic activities. While such agreements aim to restore travel connectivity, their effectiveness remains uncertain, particularly regarding their impact on public health and economic trade-offs.

First, to assess the feasibility and effectiveness of travel bubble policies, this study develops a mathematical framework that models international long-distance travel within a metapopulation epidemic model. The framework evaluates the economic benefits and public health risks associated with controlled travel bubbles, using a cost-benefit analysis to determine the optimal conditions under which such policies can be implemented. The study formulates an optimization problem aimed at maximizing the economic benefits of travel policies while mitigating the additional risks associated with increased mobility. A metapopulation model is employed to capture infection transmission dynamics across different locations, and healthcare capacity constraints are integrated into the decision-making process to ensure effective infection control. Building on this optimization framework, a sequential decision-making problem is introduced to dynamically adjust policies over time, optimizing benefits while adapting to evolving conditions. The direct lookahead method is utilized to solve this sequential decision problem, enabling proactive and efficient policy adjustments.

A case study involving Australia, New Zealand, and Japan is conducted to illustrate the practical implications of travel bubbles. The simulation includes three scenarios: dynamic border opening, dynamic border closing, and static border opening. These scenarios are designed to evaluate the impact of border policies, comparing the effects of opening versus closing and examining the advantages of dynamically adjusting border decisions over time. The findings reveal that while travel bubbles provide economic benefits, they also introduce additional infection risks that must be managed through strict monitoring and adaptive control measures. Moreover, cities with major international transport hubs, such as Tokyo and Auckland, play a critical role in travel bubble sustainability. Redirecting international passenger flows or strategically managing infection rates in these hub cities can significantly improve the effectiveness of travel bubbles. These insights highlight the importance of dynamic and flexible policymaking in the implementation of travel bubbles, ensuring that economic recovery is achieved without compromising public health.

The second component of this study shifts focus to domestic pandemic control, addressing the balance between vaccine distribution and transportation restrictions within a spatially heterogeneous mobility network. Unlike long-distance international travel, domestic transportation patterns are more complex due to frequent and high-density mobility between regions. Public transportation systems, including subways, buses, and intercity rail networks, serve as potential conduits for disease transmission, making transportation control an essential aspect of pandemic mitigation. However, overly restrictive measures can disrupt economic activities, necessitating an optimized approach that minimizes both infection rates and economic losses. At the same time, vaccine distribution plays a crucial role in mitigating infection spread, yet its effectiveness varies across regions depending on population density, healthcare infrastructure, and mobility patterns.

To optimize pandemic control at the domestic level, this study develops an optimal control framework that jointly considers vaccination distribution and transportation restrictions. The objective is to minimize total costs, which include healthcare expenses, economic losses from mobility restrictions, and vaccination implementation costs. A susceptible-vaccinated-latent-infectious-removed (SVLIR) epidemic model is formulated within the metapopulation structure to account for both transportation and vaccination control variables. Pontryagin's maximum principle is applied to find the necessary conditions for the problem solution. A case study based on Japan is conducted to evaluate the effectiveness of the proposed framework. The results indicate that combining vaccination strategies with transportation control measures leads to a significant reduction in both infections and total costs. Additionally, the effectiveness of these control measures varies by region; densely populated areas benefit more from transportation control, while less populated regions rely more on vaccination strategies. The study also identifies a synergistic effect between transportation control and vaccination distribution, demonstrating that simultaneous implementation of both strategies yields the most effective results.

The final component extends the study to a global scale, integrating international and domestic transportation with vaccine distribution through a comprehensive optimization framework. While individual countries implemented independent pandemic control measures, the interconnected nature of global mobility networks necessitates a coordinated response. Unequal vaccine distribution across countries further exacerbated disparities in pandemic recovery, with some nations experiencing vaccine shortages while others had surplus doses. To address these challenges, this study introduces a vaccine-sharing mechanism as part of the global optimization framework, enabling resource redistribution based on pandemic severity and vaccination urgency in different countries.

The global optimization model seeks to minimize total costs by simultaneously optimizing transportation restrictions, vaccination efforts, and infection control measures across multiple countries. An efficient solution method, L-BFGS-B, is employed to optimize the cost-minimization model for each country's decision-making. A case study involving 16 countries is conducted to test the feasibility and effectiveness of this model. The results show that vaccine sharing significantly reduces infection rates, accelerates transportation recovery, and lowers total costs for participating countries. Notably, the benefits of vaccine sharing vary depending on factors such as population size, transportation connectivity, and existing healthcare infrastructure. Countries with high initial infection rates, such as India and Cambodia, experience limited additional cost reductions from vaccine sharing due to their declining infection trends over time. However, engaging in vaccine sharing at an earlier stage of the infection spike could enhance cost-effectiveness by preventing outbreaks from escalating. Conversely, countries with later infection spikes, such as Laos and Singapore, do not require early vaccine sharing, highlighting the importance of timing in vaccine allocation strategies. Additionally, the study finds that vaccine-sharing mechanisms improve global transportation recovery by reallocating resources from countries with surplus vaccines to those in urgent need, leading to over 60% cost reductions in many cases. These findings emphasize the importance of international cooperation in pandemic control and provide valuable policy recommendations for global health crisis management.

Overall, this thesis presents a comprehensive framework for optimizing pandemic control measures through an integrated approach that combines transportation interventions and vaccination strategies. By addressing both national and global scales, the research provides policymakers with flexible, data-driven solutions to manage future pandemics effectively. The findings underscore the importance of international cooperation, particularly in transportation recovery and vaccine-sharing initiatives, and highlight the potential of dynamic and region-specific control measures to minimize public health and economic costs. This study contributes to pandemic management knowledge by offering a structured, multi-layered approach that aligns with public health objectives while ensuring economic resilience. The insights gained from this research provide actionable guidance for policymakers, enabling them to implement effective, data-driven policies that balance pandemic control with economic recovery.