


Original Article

Effect of flight connectivity on the introduction and evolution of the COVID-19 outbreak in Canadian provinces and territories

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Abstract

Background: The COVID-19 pandemic has challenged health services and governments in Canada and around the world. Our research aims to evaluate the effect of domestic and international air travel patterns on the COVID-19 pandemic in Canadian provinces and territories.

Methods: Air travel data were obtained through licensed access to the ‘BlueDot Intelligence Platform’, BlueDot Inc. Daily provincial and territorial COVID-19 cases for Canada and global figures, including mortality, cases recovered and population data were downloaded from public datasets. The effects of domestic and international air travel and passenger volume on the number of local and non-local infected people in each Canadian province and territory were evaluated with a semi-Markov model. Provinces and territories are grouped into large (>100 000 confirmed COVID-19 cases and >1 000 000 inhabitants) and small jurisdictions (≤100 000 confirmed COVID-19 cases and ≤1 000 000 inhabitants).

Results: Our results show a clear decline in passenger volumes from March 2020 due to public health policies, interventions and other measures taken to limit or control the spread of COVID-19. As the measures were eased, some provinces and territories saw small increases in passenger volumes, although travel remained below pre-pandemic levels. During the early phase of disease introduction, the burden of illness is determined by the connectivity of jurisdictions. In provinces with a larger population and greater connectivity, the burden of illness is driven by case importation, although local transmission rapidly replaces imported cases as the most important driver of increasing new infections. In smaller jurisdictions, a steep increase in cases is seen after importation, leading to outbreaks within the community.

Conclusions: Historical travel volumes, combined with data on an emerging infection, are useful to understand the behaviour of an infectious agent in regions of Canada with different connectivity and population size. Historical travel information is important for public health planning and pandemic resource allocation.

Key words: COVID-19, travel, modelling, Canada

Introduction

COVID-19 is a disease caused by the SARS-Cov-2 virus, which caused a pandemic that has challenged health services and governments in Canada and around the world. Major challenges include the need to strengthen public health systems, the need to augment healthcare surge capacity, closures in many countries forced by overwhelmed healthcare capacity, and high mortality over a short period of time. Closures were the most widely used public health intervention, especially prior to the availability of vaccines and therapeutics that modify the course of COVID-19.

One resource currently available to understand the dynamics of infectious disease transmission and to anticipate the effects of government decisions for the prevention, mitigation and suppression of epidemics is the application of mathematical models. During this pandemic, several mathematical models have been published around the world,¹⁻¹⁰ with different margins of error, depending on the model and the rapidly changing assumptions used, which reflect a growing understanding of the disease, changing dynamics of transmission and illness caused by COVID-19, and evolution of viral variants.

In terms of models that address mobility, Zhang *et al.*¹¹ proposed a gravity model to identify factors, particularly different transport modes, associated with the number of COVID-19 cases in Chinese cities. The authors found that the frequency of air transport and high-speed train (HST) services out of Wuhan were significantly associated with the number of COVID-19 cases in destination cities, while the frequency of coach services did not have a major influence on the number of cases. The presence of an airport or HST station was significantly correlated with the spread speed of the pandemic, but its link with the number of confirmed cases was quite weak and disappeared when other factors were controlled for. Huber *et al.*¹² evaluated a probabilistic choice behaviour (Huff) model to estimate airport catchment areas in the United States in the absence of empirical local human mobility data and in data-limited public health scenarios. They found that the Huff model could be used to estimate airport catchment areas at any level of geography within a reasonable spatial scale. Watts *et al.*¹³ predicted the spread of infectious diseases by evaluating human mobility patterns through several mechanisms (e.g. mobile devices, social media, commercial air travel). A simpler model was proposed by Chen *et al.*¹⁴ who established China's mobility network using a flight dataset and proposed a model without epidemiological parameters to indicate the risk of spread through the network, which was termed as epidemic strength. The authors considered a mobility network based on the OpenFlights airport database. They extracted airport and route data for cities across China, covering 185 airports and 1515 routes, to construct a human mobility network, where each node denoted an airport, and each arc denoted a flight route.

The Government of Canada has been using mathematical modelling to guide public health action.¹⁵ Hurford *et al.*¹⁶ documented that travel restrictions to enter Newfoundland between March and June 2020 reduced the mean number of COVID-19 cases by 92%. Ding *et al.*¹⁷ proposed the Flight-SEIR (susceptible, exposed, infected and recovered) model to estimate the number of imported cases based on air traffic volume and test positivity rates. During the COVID-19 pandemic, the emergence

of variants of concern (VOC) has been reported, including Alpha, Beta, Gamma, Delta and Omicron.¹⁸ Those VOC initially spread around the world through travellers between and within countries. Tracking air travel patterns between and within any country allows public health decision-makers to identify and predict potential outbreaks, and to quickly implement public health measures that contain the transmission of respiratory infections.

Our research aim was to evaluate the effect of domestic and international air travel passenger volume patterns on the COVID-19 pandemic in Canadian provinces and territories.

Materials and Methods

Data extraction

Air travel data were extracted from 'BlueDot Intelligence Platform', a platform developed by Canadian software company BlueDot Inc., that allows licensed users to query and download annual data displayed by month, for passenger volumes of commercial flights (<https://bluedot.global>). Data can be extracted for any point of origin or destination identified by city, province/territory or country, including locations within Canada or any other part of the world. Passenger volume data from 2010 to September 2021 were manually downloaded from the BlueDot platform, for a total of 133 datasets, which were consolidated into four main datasets: (i) number of passengers by city of origin for passengers that flew from any city in the world to Canada, displayed by month; (ii) number of passengers by destination city for passengers that flew from any city in the world to Canada; (iii) number of passengers by origin city for passengers that flew from Canada to any city in the world; and (iv) number of passengers by destination city for passengers who flew from Canada to anywhere in the world. As the data includes both itineraries purchased via airline and travel agency, it includes connecting stopover flights. Connections are restricted to stopover flights made within 24 hours. After 24 hours, the air travel is counted as separate flights.

In addition, daily COVID-19 datasets for Canada were downloaded from the GitHub COVID-19 Canada Open Data Working Group.¹⁵ From the provincial and territorial time series section, data were downloaded for active cases by province or territory (the dataset includes date active, cumulative cases, cumulative recovered, cumulative deaths, active cases), new cases by province or territory, mortality or number of deaths by province or territory and COVID-19 cases recovered.

Finally, daily COVID-19 data at the global level were downloaded from the GitHub COVID-19 Data Repository by the Centre for Systems Science and Engineering (CSSE) at Johns Hopkins University.¹⁹

Population data for the world and Canada were downloaded from Kaggle²⁰ and Statcan,²¹ respectively.

Describing, profiling and cleaning the datasets

Data description was done through the Google Colab platform in the Python programming language. For Canadian COVID-19 data, missing data accounted for less than 0.5% of all downloaded time series and were omitted from the analysis. For

the data set of active cases, a rolling mean process was performed to adjust for delays and periodicity in case reporting. Case values were averaged over a 14-day period.

Modelling process

To evaluate the effect of air travel and passenger volume on the number of infected people in each Canadian province and territory, both Canadian domestic and international passenger air travel volume were considered. The infection model is based on an estimation of the number of newly infected people per day and the number of infectious people every day. It is also important to note that the number of infectious people is estimated as the sum of local infectious persons (which is equal to the number of infectious persons living in the study area that became infected due to community transmission), plus a proportion of the people arriving to a Canadian province or territory through air travel that are potentially infectious based on the number of active cases that are within the infectious period (7 days in total for asymptomatic people, or 2 days prior to the symptoms onset and 5 days after the start of symptoms) in the country the flight originated from (imported or non-local cases).

The number of susceptible individuals is based on the population of a certain area and the cumulative number of infected people in the same area, even though they may have recovered or died. We consider the following relationships among these parameters:

$$S(t) = N_0 - E(t), \quad (1)$$

where $S(t)$ is the number of susceptible people at time t . N_0 is the population of a province or territory, and $E(t)$ is the cumulative number of infected people. To obtain the number of people infected on a certain day, the number of people still susceptible on that day must be known. After m days a person is not infectious (people in the postinfectious period include both those that died and those that recovered). Thus, having the daily number of incident cases $\Delta E(t)$, we can find the number of non-infectious people at time $t + m$. By accumulating the incident daily cases and the change in the number of recovered/dead cases over time we can estimate the number of infectious patients per day. To relate the newly diagnosed people at day t , $\Delta E(t)$, with the infectious people at day t , $I(t)$, we propose the following expression:

$$\Delta E(t) = \alpha I(t - \Delta t) S(t - \Delta t), \quad (2)$$

where α is a proportionality constant to be identified for each Canadian province or territory, Δt is used to indicate the latent period, and time t is the date of SARS-CoV-2 diagnosis. The α constant is related to the epidemic curve using the real data of each province or territory throughout the COVID-19 pandemic. The epidemic curve depends on the basic reproduction number and the behaviour of the disease in each area. The reproductive number is influenced by a myriad of factors, including host-pathogen interactions impacted by vaccination and variant distribution. In addition, any enacted policies that restrict mobility or the frequency of contact among people will modify this number.

As mentioned above, the model requires the number of all infectious cases, including the local and non-local (travelling)

infectious patients who may be present in the region at time t . We find the number of infectious people that may arrive in Canada on a certain date and consider that number as an estimate of the number of infectious non-local patients (imported cases). We then define local transmission, $I_o(t - \Delta t)$, as the number of infectious people that become infected due to community transmission and the imported cases, $I_e(t - \Delta t)$, as the number of imported infectious cases. The total number of infectious cases in each Canadian province or territory is obtained from the sum of local transmission and imported cases, i.e.

$$I(t - \Delta t) = I_o(t - \Delta t) + I_e(t - \Delta t). \quad (3)$$

To quantify the imported cases, $I_e(t)$, we estimate the number of infected people arriving from all countries to a specific Canadian province or territory on a certain date. Thus, we define $I_{e,j,k}(t)$ as the number of infected people coming from country j to the province/territory of Canada k . $I_{e,j,k}(t)$ can be estimated using the number of air travel passengers coming from country j to the province or territory of Canada k and the fraction of these passengers expected to be infectious according to the epidemiological information and population of the country j . Thus, the newly infected people, $\Delta E(t)$, defined by Eq. (3), can be derived by the following expression:

$$\Delta E_k(t) = \alpha_k [I_{o,k}(t - \Delta t) + \sum_{j,k} I_{e,j,k}(t - \Delta t)] S(t - \Delta t). \quad (4)$$

Results and discussion

Figure 1 illustrates commercial air travel passenger volumes (arrivals) to each province or territory in Canada, combining domestic and international travel. Over the course of a given year, similar patterns can be seen in passenger volumes, which reflect seasonal variation in travel, with high volumes during cold weather months, as well as spring and summer school holidays (Figure 1).

A clear decline in passenger volumes can be seen beginning in March 2020, which coincides with the initiation of public health policies, interventions and other measures taken to limit or control the spread of COVID-19 (Figure 2). As the measures were eased, some provinces and territories saw small increases in passenger volumes, although the number of passengers did not return to levels observed at the beginning of 2020.

Figures 3 and 4 show the relationship between new cases and the number of infectious people in the left and middle columns, and the relationship between local transmission and imported cases in the right column. Provinces and territories are grouped into those with large ($>100\,000$ confirmed COVID-19 cases and $>1\,000\,000$ inhabitants) and small numbers of infected people and population ($\leq 100\,000$ confirmed COVID-19 cases and $\leq 1\,000\,000$ inhabitants) in Figures 3 and 4, respectively.

The change in line colour from dark to light tones in the right column of Figures 3 and 4 represents the course of time associated with real data, from the earliest (darkest colour) to the most recent (lightest colour) stages in the pandemic. Note that at the initial stage of the pandemic, the first peaks were driven by imported cases (the line trends vertically, parallel to the Y axis). After these initial days, we can see in the right column of Figure 3 and 4 that the local transmission is much higher (the

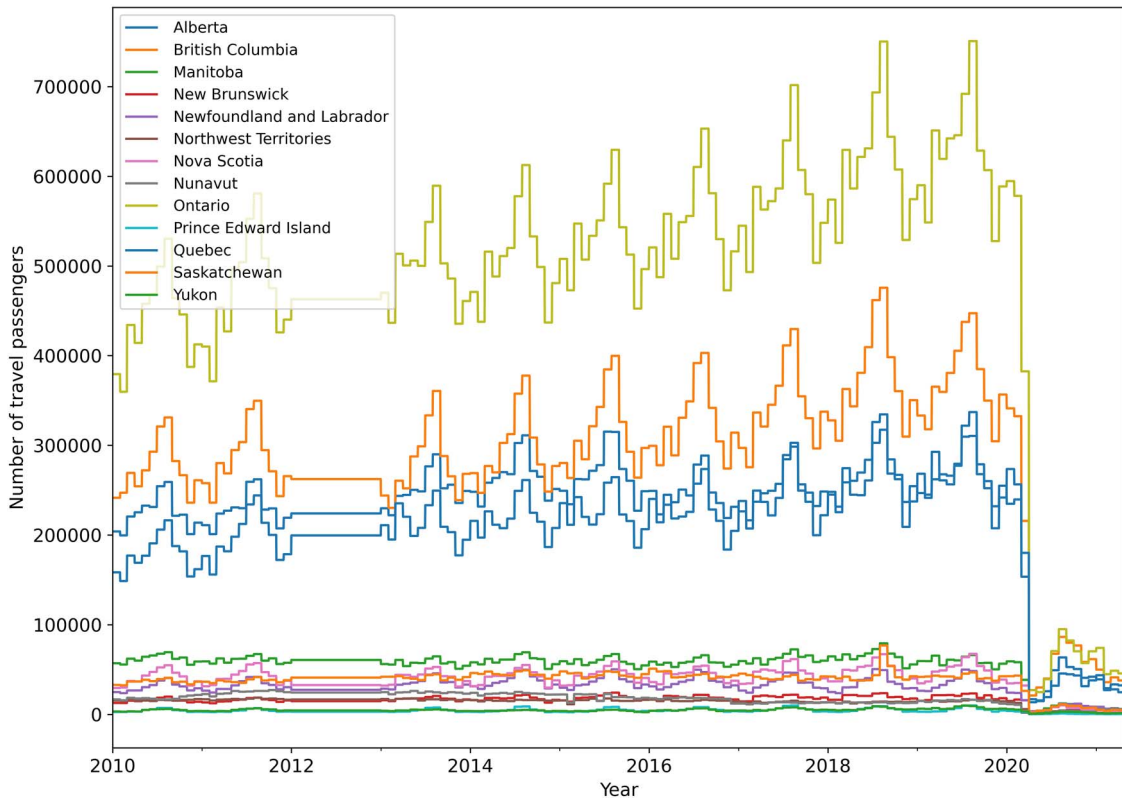


Figure 1. Monthly arrivals of air travel passenger volumes to each Canadian province or territory from January 2010 to September 2021.

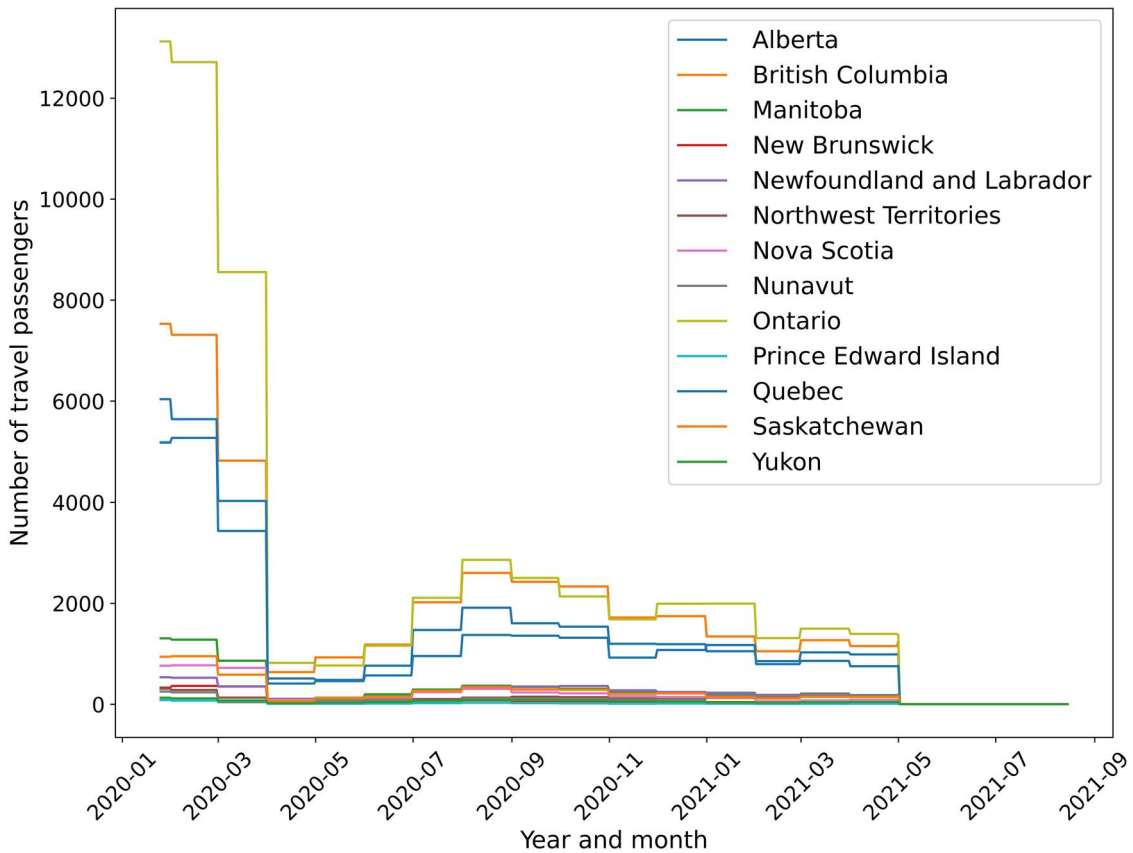


Figure 2. Monthly air travel passenger volumes over the course of the pandemic displayed by province or territory.

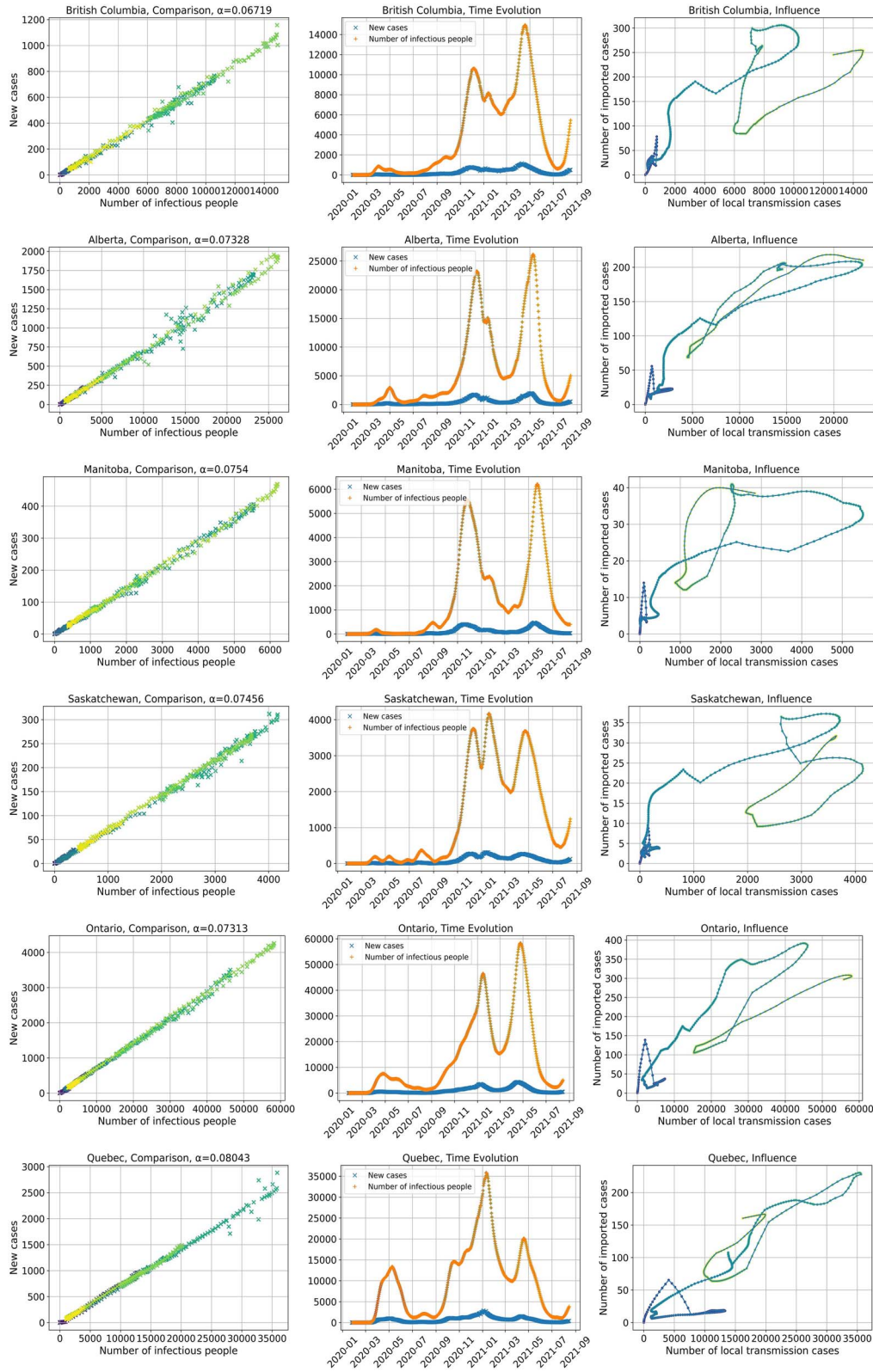


Figure 3. Relationship between new cases and number of infectious people, and local transmission and imported cases in British Columbia, Alberta, Manitoba, Saskatchewan, Ontario and Quebec. Legend: Left and middle columns: the relationship between new cases and number of infected people. Right column: the relationship between local transmission and imported cases. Dark colours represent the earliest data and light colours represent the most recent data.

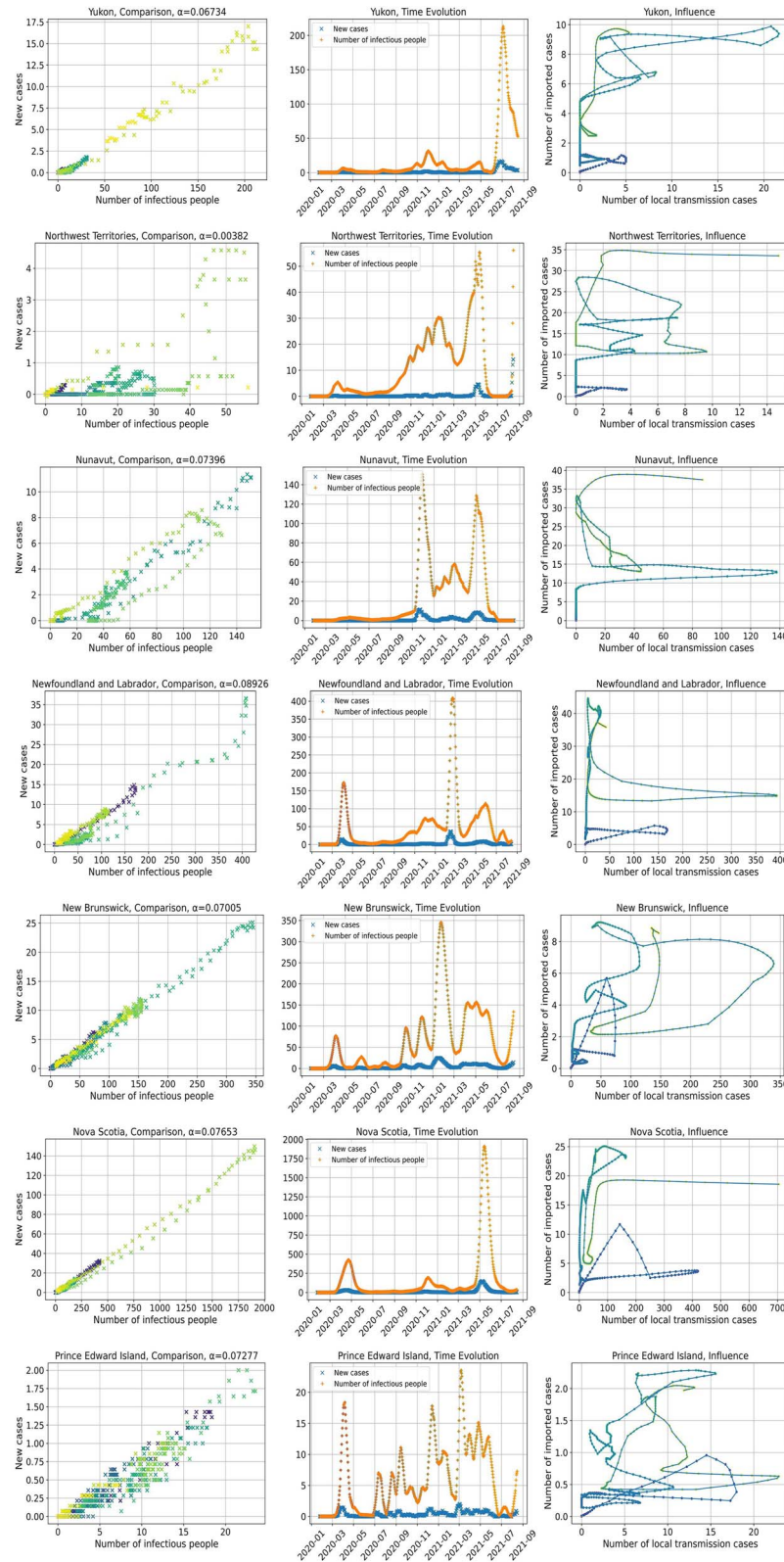


Figure 4. Relationship between new cases and the number of infectious people, and the local transmission and the imported cases in Yukon, Northwest Territories, Nunavut, Newfoundland and Labrador, New Brunswick, Nova Scotia and Prince Edward Island. Legend: Left and middle columns: The relationship between new cases and the number of infected people. Right column: The relationship between local transmission and the number of imported cases. Dark colours represent the earliest data and light colours represent the most recent data.

line trends horizontally, parallel to the X axis) than imported cases, which means that after some period the pandemic evolves according to local transmission patterns. It also shows how several public health policies, interventions and other measures taken to limit or control the spread of COVID-19, as well as relaxation of closures, result in a steeper vertical line, related to the importation of cases, or a more horizontal line, related to local transmission (right column Figure 3).

During the early phase of disease introduction, the burden of illness is determined by the connectivity of jurisdictions. In provinces (Figure 3) with a larger population and greater connectivity, the burden of illness is driven by case importation, although local transmission rapidly replaces imported cases as the most important driver of increasing new infections. The introduction of public health measures and interventions resulted in a decline in the number of new infections, and partial relaxation of these measures allows for the importation of new variants, hence the complex evolution of disease burden as seen in Figure 3.

International travel has been documented to facilitate the spread of SARS-CoV-2 worldwide,^{22,23} including each new VOC, mainly during the asymptomatic or presymptomatic phase of the disease (initially referred to as undocumented infections²²). The subsequent closure of borders or travel bans implemented by most governments around the world resulted in a reduction of imported cases and subsequent deaths.^{24,25} However, estimating the real impact of each preventive measure or restriction is challenging as there were several strategies implemented simultaneously during the first year and a half of the pandemic, such as mandatory facemask usage and social distancing (e.g. full or partial lockdowns, online learning, remote working, gathering restrictions, self-isolation, etc.) with different estimates of the impact of each measure.²⁴⁻³¹ Local transmission can be explained by the mobility pattern within these provinces and superspreader events as seen in India and Italy.^{23,30,31}

In smaller jurisdictions, a steep increase in cases is seen after importation, leading to outbreaks within the community. The right column of Figure 4 shows that in smaller provinces and territories a discrete introduction event is followed by various degrees of outbreak development and additional peaks are dependent on subsequent introductions. The pattern observed in those smaller jurisdictions shows steeper vertical lines parallel to the Y axis compared to larger jurisdictions, that reflect that the epidemic curve was mostly influenced by imported cases, with sudden horizontal lines parallel to the X axis depicting an outbreak.

Historical passenger air travel volumes and connectivity patterns are important for public health planning and can inform public health pandemic resource allocation. For example, Huber *et al.*¹² have proposed that a potential strategy is defining airport catchment areas to assess the possibility of local-level spread of outbreaks because 'they could help approximate airports where an infected individual is most likely to travel outbound from the epicentre of an outbreak, and the geographic area where an infected traveller might go after deplaning at their destination'.

Publications from around the world describe multiple strategies that could work in a future epidemic/pandemic that behaves similarly to SARS-CoV-2.³² For example, a potential strategy that could be implemented by Canada would be to deploy point-of-care rapid diagnostic testing for all arriving travellers, where each person could be tested upon arrival and provided

with at least two more rapid antigen tests to self-screen at home on the third and sixth day post-arrival. Larremore *et al.*³³ demonstrated that, for viruses with infection kinetics similar to SARS-CoV-2, the most critical points are the speed of reporting and the effect of repeated population screening. It is important to mention that SARS-CoV-2 was a new virus and all diagnostic and rapid testing, therapeutics and vaccines were developed within an unprecedented timeframe. However, once those rapid tests were available, none of them were provided to passengers upon arrival nor for repeated testing at home. For a few months, Canada implemented home/hotel quarantine until negative tests were returned. The government then lifted the restriction for fully vaccinated travellers and implemented random PCR testing at arrival for passengers on international flights, and the results were often available 4 or 5 days after sample collection. As other authors have previously described in the literature,^{6,34,35} international arrivals played an important role in transmission during the COVID-19 pandemic, including the spread of variants of concern. Therefore, a cost-effective strategy for the government and passengers could be the implementation of universal rapid point-of-care testing and repeated testing that can limit the spread of COVID-19.

Our study has several limitations. The first limitation relates to information about the epidemic curve of COVID-19 for each country. Second, the number of COVID-19 cases is likely underestimated, in particular, after the introduction of rapid-point-of-care tests. The data related to COVID-19 cases is based on public health reports for each province and territory, and this information was based on confirmed cases from public and private laboratories. The passenger volume data cannot link travel for individuals who book multiple tickets on multiple carriers for long journeys. As the data includes both itineraries purchased via airline and travel agency, it includes connecting stopover flights. Connections are restricted to stopover flights made within 24 hours. After 24 hours, the air travel is counted as separate flights. Finally, the available data were limited to a monthly average number representing air travel passenger volumes from different countries travelling to each Canadian province. We had to estimate the daily number of passengers based on this information.

Conclusions

This research demonstrates the impact of flight connectivity on the introduction and evolution of the COVID-19 pandemic. Historical air travel volumes, combined with data regarding an emerging infection, are useful for the prediction of early phases of pandemic and the introduction of an infectious agent into Canada. Understanding how the COVID-19 pandemic evolved and the relationship between imported cases and community transmission is an opportunity for governments to implement strategies that can help control the spread of the disease at international airports. Historical travel information allows for proactively enacting public health measures in smaller jurisdictions before the arrival of cases.

Authors' contributions

Substantial contributions to the conception and design of the work: All authors. Acquisition: R.H., D.M., N.O., H.I., Z.V.R.

Analysis: RH, DM. Interpretation of data for the work: All authors. Drafting the work: R.H., D.M., Y.K., Z.V.R. Revising the paper critically for important intellectual content: N.O., H.I., S.S. Final approval of the version to be published: All authors. Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved: All authors.

Supplementary Data

Supplementary data are available at *JTM* online.

Data extraction process is described in [Supplementary File 1](#).

The code that we used for this analysis can be found at this link: <https://github.com/nathaliaortega/role-of-travel-mobility-on-COVID-19-Manitoba>

Air travel data are derived from outputs of BlueDot's Intelligence Platform and were accessed through a paid licence to BlueDot Inc. BlueDot's outputs are informed by proprietary data from the International Airport Transport Association (IATA). Due to copyright agreement, the authors are unable to share the dataset. For verification of findings, the air travel data are available upon request to BlueDot Inc. through the coauthor Harpa K. Isfeld-Kiely (Harpa.Isfeld-Kiely@umanitoba.ca).

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Conflict of interest

NCCID paid a licensing fee to BlueDot Inc. to access flight data. BlueDot Inc. had no role in the study design, data collection and analysis, decision to publish or preparation of the manuscript. The authors have no conflict of interest to declare.

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