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On the degree of synchronization between air transport connectivity and COVID-19 cases at worldwide level

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ABSTRACT

COVID-19 is one of the most impactful pandemics in recent history, not only in terms of direct casualties but also regarding socio-economic impact. The goal of our study is to investigate the degree of synchronization between the number of confirmed cases in specific countries, on one hand, and how/at which stage these countries adapted their air transportation operations, on the other hand. We investigate the global air transportation system as a network of countries whose edges represent the existence of direct flights. Aggregated analysis of this country network and its evolving dynamics leads to novel insights regarding the synchronization with the number of confirmed cases; finding that most country borders were likely closed too late. We believe and hope that our analysis leads to a more efficient/effective prevention and control of future epidemics.

1. Introduction

The 20th century was undeniably the century of aviation in transportation, from the design of the first aircraft (The Atlantic, 2020), the engineering of increasing effective engine technology (notably the invention and refinement of jet engines), to the exploitation of efficient hub-and-spoke networks (Gillen and Morrison, 2005), ending with predicted annual growth rates between 2% and 5% (Lee et al., 2009). The whole aerospace industry has not only revolutionized the way we travel around the world; but also significantly changed our view on how we see the world. Nevertheless, the enhanced long-distance mobility provided by aviation comes with a set of challenges and problems. Except from ongoing discussions that aviation is harmful to the climate and nature, there is a second catch. Since air transportation can bridge long distances in a short amount of time, the risk for diseases spreading is becoming higher in recent years (Brockmann and Helbing, 2013). We refer to a few recent examples of outbreaks, which were on the edge to turn into a pandemic: MERS 2012 (Zaki et al., 2012) and Ebola 2014 (Bogoch and et al., 2015). Earlier diseases had devastating and harmful effects; their impact, however, could mostly be reduced to the regional level: International organizations and communities were able to cut transmissions of the disease at early stages, which prevented a full pandemic.

COVID-19, on the other hand, had a different outcome. Within the first few months of 2020, the disease was able to quickly spread to almost all countries and induced travel-bans and lock-downs at an unprecedented, perhaps inconceivable scale. As of September 28th, 2020, COVID-19 has caused approx. 33 million global cases and almost one million deaths which are believed to be related to the disease. Fig. 1 gives an overview of the major events during the pandemic outbreak throughout the first five months of the year 2020. The reactions of countries towards the advent of COVID-19 have been quite different, leading to few success stories, while other countries have been hit rather hard by the pandemic. The degree of success for fighting a contagion at an early stage can largely be attributed to the establishment of flight restrictions. Strict flight restrictions are mostly effective at early stages of an epidemic/pandemic, when the disease is not prevalent inside a country yet. Fig. 2 visualizes the degree of country-specific flight restrictions during COVID-19 in May 2020. We can observe that more than half of all countries worldwide had full or partial flight restrictions, which limited the international travel significantly. Recent studies have analyzed the role transportation systems played mainly inside China (Kraemer et al., 2020; Li et al., 2020b; Chinazzi et al., 2020; Cheung et al., 2020), combining air transportation and high-speed railway systems, which are the prevalent mid-range transportation modes in China. Moreover, some studies aimed at developing disease spreading models,

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which quantify the risk of disease spreading from China to other countries (Christidis and Christodoulou, 2020) and the role government policies had on reducing the number of infections and effects on economic growth (Hsiang et al., 2020). Finally (Sun et al., 2020), used tools from network science to investigate how the disease affected on the structure of air transportation as a fractal system.

In this study, we address the following question: What degree of synchronization can we find between air transport connectivity and the number of confirmed COVID-19 cases? Given the known importance of air transportation on disease spreading, together with the fact that early cases of COVID-19 were identified at the beginning of January, one would have expected, that the aviation system would have been (at least partially) locked down *before* the disease aggressively spread around the world; travel restrictions are critical particularly at early stages of an outbreak (Kraemer et al., 2020). The two major decision makers to be considered here are countries (governments) and airlines. Countries have the political power to protect their people by closing borders, mainly by the means of invoking travel bans on part of the population. Airlines, on the other hand, being mainly profit-driven, need to meet the demand of travelers, in order to reach sufficient load factor, to be profitable. Here, we focus on the role of countries, by trying to identify the order of events, involving the closure of country borders and the temporal evolution of COVID-19 cases. Given our hypothesis, one would expect that the operations of aviation would have been significantly reduced before the virus entered the country. The findings in our study, however suggest completely opposite: Most operations were ceased only long after the first cases were reported. Our study is based on actual flight data for the first five months of the year 2020. Overall, this study investigates the two-way relationships between air transportation and COVID-19: on one hand, air transport (connectivity, or policies of cutting air transport connectivity) clearly affects the spread of COVID-19. On the other hand, this study also takes a look at the impacts of COVID-19 on aviation.

We give a brief overview on the structure of our manuscript. Section 2 reviews related studies on disease spreading over air transportation networks. Section 3 reports the results of our study regarding the synchronization of air transportation operations and COVID-19 cases. Section 4 concludes this study and provides an outline of possible future directions.

2. Literature review

There is broad range of pre-COVID-19 literature on disease spreading. Throughout the past two decades, many methods and tools designed within the area of network science have proven beneficial for the analysis of disease spreading over complex networks; applied to seasonal influenza (Khan et al., 2009), Ebola (Pigott et al., 2014), SARS/MERS (Wong et al., 2015; Poletto et al., 2016), and others. These results include, among others, stochastic computational frameworks (Colizza et al., 2006), the global epidemic and mobility computational model (Balcan et al., 2010), an airline importation risk model (Huang et al., 2012), compartment-based models for disease spreading using airline data (Hwang et al., 2012), and an airport risk index based on effective distance (Brockmann and Helbing, 2013). The readers are referred to these seminal papers and references therein.

In the following, we review the recent body of literature covering COVID-19 and (air) transportation. First, a large part of this literature is concerned with the question of how transportation infrastructure could help to predict the arrival of COVID-19 in a specific region. For instance (Christidis and Christodoulou, 2020), assessed the risk of spreading COVID-19 outside China, by analyzing historical flight data for the year 2016–2019. It was found that the risks associated with local infections was highly underestimated (Gilbert and et al., 2020). put a focus on African countries and estimated the risk of importing COVID-19. The capacity of a country to detect and respond to cases was determined with two indicators: Preparedness, using the WHO International Health Regulations (IHR) Monitoring and Evaluation Framework (MEF); and vulnerability, using the Infectious Disease Vulnerability Index (IDVI). The IHR MEF is composed of a mandatory self-reporting of capacity, and three voluntary components (the Joint External Evaluation, the after-action review, and simulation exercises). The mandatory self-reporting of capacity contains 24 indicator scores: Legislation, IHR coordination, laboratory, surveillance, human resource, national health emergency framework, health service provision, communication, points of entry, zoonoses, food safety, chemical events, and radiation emergency. The country's capacity to deal with the importation and spread of COVID-19 is derived by averaging these indicators, except the last four. The IDVI was introduced to account for other indirect factors, such as demographic, environmental, socioeconomic, and political conditions.

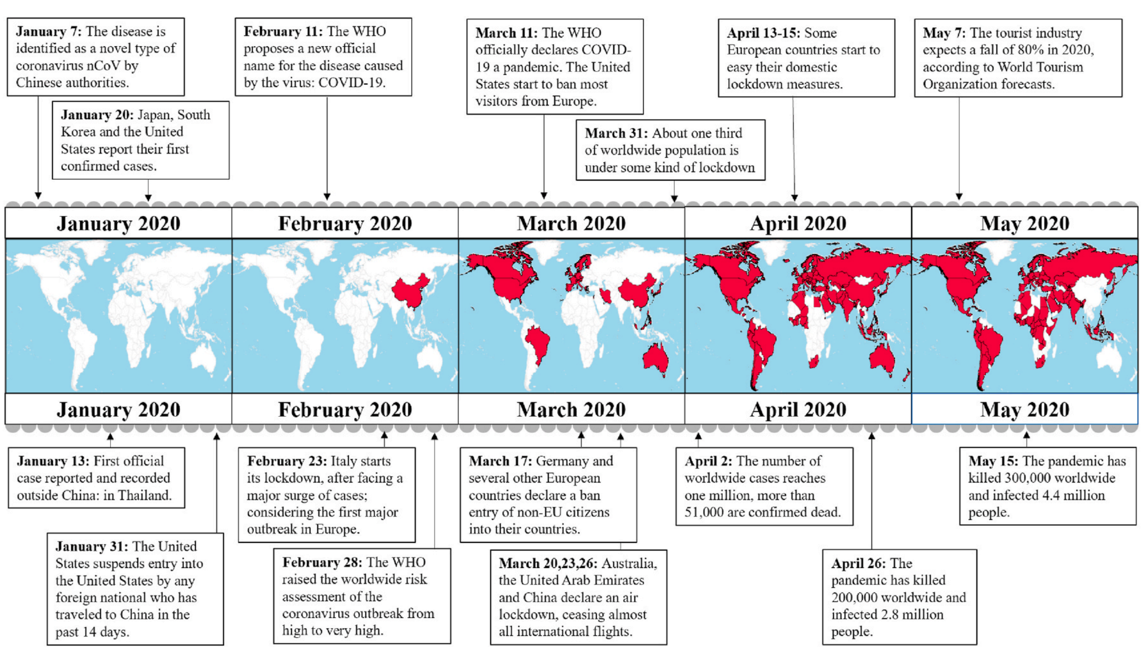

Fig. 1. Timeline of major events regarding the COVID-19 pandemic in the first five months of the year 2020. The five maps in the center of the figure highlight the countries which had at least 100 new infections per day on the 15th of the month.

Both indicators range from zero to 100, with increasing level of capacity and decreasing vulnerability (Zhang et al., 2020). found that the frequencies of transportation (here, high-speed rails and air services) out of Wuhan were likely related to the number of report cases in destination cities. In addition, several researchers used compartmental meta-population models for making predictions about the time and extent of an arrival of COVID-19 in distinct regions (Coelho et al., 2020; Hossain et al., 2020; Li et al., 2020a; Nikolaou and Dimitriou, 2020; Gomez-Rios et al., 2020). Notably, these studies take different research questions compared to ours; while they are concerned with the prediction of disease arrivals (i.e., what might happen in the near future), we are instead interested in the historical synchronization of flight reductions (i.e., what happened under the actual reactions of different countries).

A second stream in the literature concerns the investigation of contagion control measures; with the ultimate goal of analyzing how policy changes possibly affect the spreading of a contagion (Kraemer et al., 2020). used real-time travel data from one of the biggest internet companies in China, Baidu, to investigate the impact of control measures on the COVID-19 spread in China at the start of 2020. It was shown that travel restrictions are particularly useful in the early stage of the outbreak compared with the stage that the outbreak is more widespread. Here, the early stage refers to January to February; a period at which time travel bans for long-distance transportation and other measures would have been more useful to prevent turning the epidemic outbreak into a global pandemic. The exact tipping point, however, is difficult to identify (Li et al., 2020b). focused on the roles of undocumented cases on the overall prevalence and pandemic potential of COVID-19, using observations of reported cases in China, together with mobility data from Tencent, a networked dynamic meta-population model, and Bayesian inference. They estimated that approximately 86% of all infections were undocumented before the travel restrictions implemented in January 2020, and the transmission rate of undocumented infections were around 55% more than that of the known cases (Chinazzi et al., 2020). used a metapopulation model to study how travel restriction and quarantine have an effect on COVID-19. It was found that Wuhan's quarantine has delayed the spread for a few days inside China (Hsiang et al., 2020). applied reduced-form econometric methods to measure the effects of anti-contagion policies on economic growth as well as the growth rate of COVID-19 infections, which were found to substantially slowed the growth of COVID-19 infections (Guan et al., 2020). investigated control measures on a trade modelling framework, reporting that the number of countries imposing restrictions are most sensitive to the lockdown's duration (Nakamura and Managi, 2020). compared three scenarios of air travel restrictions during COVID-19 and revealed the large-scale risk for all countries; concluding that each airport should be prepared for taking actions and countermeasures (Oum and Wang, 2020). investigated policies for COVID-19 regarding optimal lockdown and travel restrictions (Zhang, 2020). proposed the PASS approach for policymakers taking into account future public health threats. These studies are different from ours in a sense that they perform scenario analysis - usually at a regional level, to make suggestions for how stakeholders should react facing future diseases.

Finally, a few studies were concerned with the impact of COVID-19 on air transportation and other areas of peoples' lifes (Suau-Sanchez et al., 2020). estimated the impacts of COVID-19 on commercial aviation, focusing on three aspects: supply, demand (passenger behavior), and regulatory impacts. It was found that the future ticket prices and the future development of air freight are highly uncertain (Beck and Hensher, 2020). discussed the impact of COVID-19 on activities in Australia, especially emphasizing the benefits of working from home. Possible routes for a safer transportation future include the introduction of immunity certificates (Chen et al., 2020) and the establishment of backbone multi-modal networks (Tardivo et al., 2020).

3. Results and discussion

In order to perform this study on the degree of synchronization, we downloaded aircraft-specific flight data from http://www.flightradar24.com. The data covers almost 3000 airports and more than 100 airlines. We have extracted the daily flight networks for being able to analyze the evolution over time. The data in our study covers a period of more than four months, starting from January 5th, 2020 and ending with May 15th, 2020. Fig. 3 provides snapshot visualizations of the global air transportation country network (Wandelt and Sun, 2015) for two selected dates: January 1st, 2020 (left) and April 30th, 2020 (right).

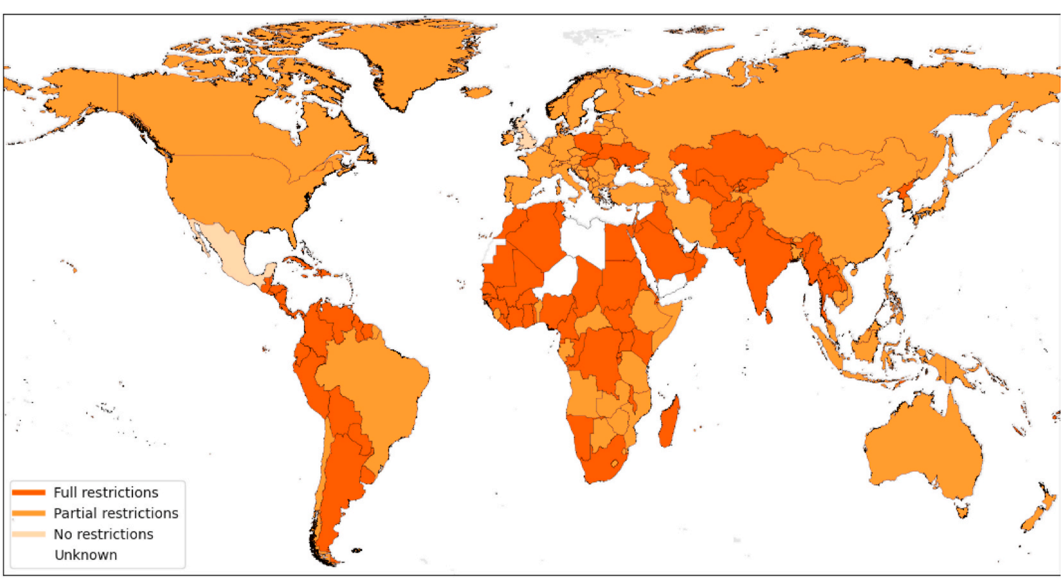

Fig. 2. Flight restrictions on countries as reported by IATA (May 21st, 2020). Half of all countries worldwide have full/total restrictions (in darker orange color), which means that airports are closed to all international flights/passengers. Partial restrictions (in light orange color), as implemented with the majority of remaining countries, which often accept the flights of country nationals, permanent residents (green-card holders), and other (distinct) exceptions. A few countries have no restrictions reported (in lighter orange color) or have unknown restrictions according to IATA (without color). See https://www.iatatravelcentre.com/international-travel-document-news/1580226297.htm for details. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

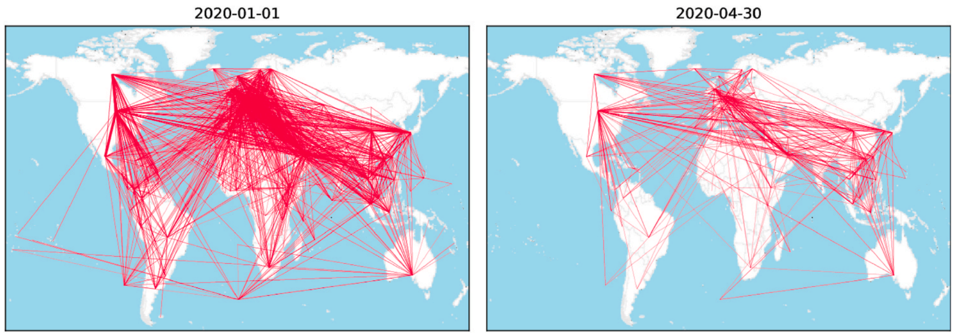

Fig. 3. Comparison of the air transportation country networks for January 1st, 2020 (left) and April 30th, 2020 (right). All countries are represented by nodes and there exists a link between two countries of there is at least one international flight. A significant drop in the network connectivity can be observed throughout the COVID-19 pandemic.

It can be seen that the connectivity of the international country network drops significantly throughout the COVID-19 pandemic.

Furthermore, the impacts of COVID-19 on air transport are more profound on the international market than in the domestic market. This distinguishing effects can be seen more clearly in Fig. 4; with an example of three major criteria explored and analyzed in our study. For each country (Australia, China, Germany, and United States),[1] these three indicators are plotted as a time series using a log scale. The first indicator is the cumulative number of confirmed cases in the country (blue color). All countries reveal a two-stage growth pattern, with an initial growth towards a few hundred cases, just to turn into a full-scale epidemic in each country within a few weeks; only the slope and the initial growth date are different among countries. The second indicator in our study is the number of international flights (green color). We can observe an expected seasonality of the number of flights; until a specific point where the number of international flights drops significantly. Similarly, the third indicator reports the number of domestic flights (orange color). The dashed, vertical line represents the approximate time of drop in the number of international flights for a country.

For these motivating examples, it can be seen, that for all four countries, the second stage of the domestic epidemic was already reached when the airlines/governments decided to cancel these flights. It is suspected for several decades that air transportation plays a key role for turning a local epidemic into a global pandemic; because it allows long-distance travel in short amount of time; thereby reducing the effective distance between remote places. Given the limitation of the data, we cannot tell the load factors of aircraft which flew before the lock-down and its effect on the two indicators. It is reported that some airlines were flying (essentially) empty aircraft, in order to not lose their slots at the airports. Other airlines were operating off-schedule flights for conducting take-home missions of passengers stranded in remote places; even into times when travel bans were active. Nevertheless, the operations of these aircraft on its own, even if they were not fully loaded, puts the crews and therefore the destination countries at high risk. Therefore, these four examples motivate us to analyze the effect of synchronization between air transport operations and the increase in confirmed cases in this study.

The discussion of four example countries leads to the question whether these patterns are general and they holds for more countries. Accordingly, we investigate the normalized curves further in Fig. 5. The data points for each country are normalized in a range from 0.0 (minimum) to 1.0 (maximum); a moving average filter with window size equal to seven was applied in order to remove outliers and reduce the effect of weekly seasonality; the window size of the moving average is set to seven. The following insights can be obtained: First of all, China and South Korea are outstanding from the other countries given the early rise in the number of reported cases, Fig. 5 (top), as well as with the early reduction of the number of international flights and domestic flights, Fig. 5 (middle, bottom). The vast majority of other countries has a significant delay in all three indicators. The number of confirmed cases in Japan and Russia grows significantly in May 2020, where Russia shows an exponential growth behavior. Japan is among the first countries to impose international travel bans, while Russia imposed restrictions on international flights rather late (almost the same, on average, as the pattern with all other countries). Regarding flight restrictions on domestic markets, both Japan and Russia reacted quite late among all countries in the world.

In the remaining part of this study, we analyze this transition during the COVID-19 pandemic further; with an emphasis on the synchronization and type of events. First, we take into account the degree, a node importance metric used in network science, which measures the number of direct neighbors. In our case, the degree of a country in the network corresponds to the number of destination countries reachable with a direct flight. Fig. 6 depicts the spatial distribution of countries and how they reacted to COVID-19. The color of a country corresponds to its degree on April 1st, 2020, divided by the maximum degree throughout the period of this study. It can be seen that the majority of countries have decreased their number of (country) destinations significantly during the pandemic; many of these countries below 25%. A few countries stand out with remaining the degree of connectivity at a higher level, e. g., Mexico, Peru, Belarus, and Iceland. We discuss two of these examples below. Iceland stands out in the way it dealt with COVID-19; having tested half of its population and performed genetic sequencing of all positive-tested cases discovered. The historical experience of the Icelandic government with the pandemic influenza in October 1918 (more than 100 years ago), has led to the design of a national pandemic preparedness plan at the beginning of 2020, several months before the actual disease arrived at Reykjavik. While COVID-19 was emerging, the government was careful to keep the borders open for tourists – a major source of income to the country. Combined with the domestic efforts on surveillance, tracking, and analysis, this strategy turned out a success story. Peru, on the other hand, was hit extremely hard by COVID-19, leading to the highest mortality of all countries in the world. One major reason why the disease was not successfully contained in the country is the poverty of its population. While the government did try to fight the pandemic with local lockdowns, the majority of its population (about 70%) works in the informal ("underground economy") sector; accordingly, they (need to) try everything to keep their income high. These two exemplary case studies highlight that the drivers and effects of (not) controlling the travel restrictions are manyfold, which deserves further future analysis.

In the next experiment, we aim to understand the process of flight reductions with respect to the connectivity intensity of a country (i.e.,

[1] These four countries were selected to represent the effect of the pandemic on distinct regions of the world, covering Asia, Europe, North America, and Oceania.

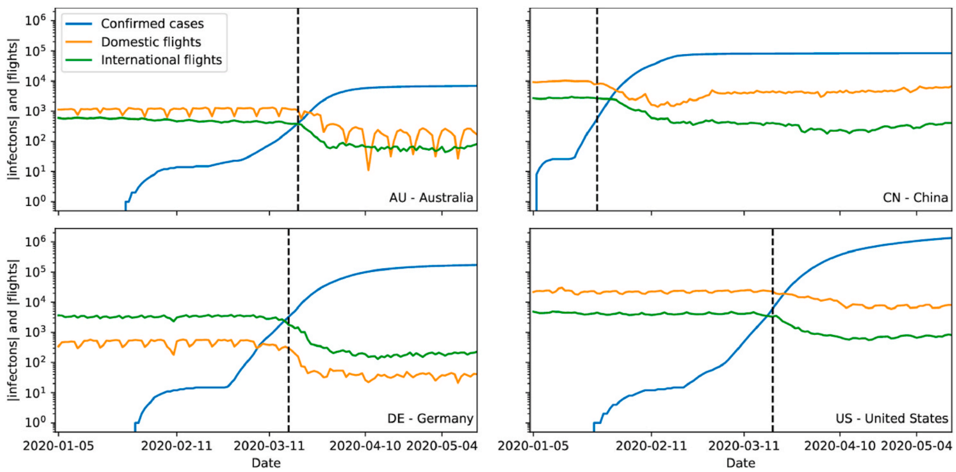

Fig. 4. A motivating example based on three indicators: the number of confirmed cases (curves in blue color) and the count of domestic/international flights (orange/green curves) for four selected countries (Australia, China, Germany, and United States.) The x-axis shows the timeline along the COVID-19 outbreak, the y-axis shows the number of infections, domestic flights, and international flights in a log scale, and the vertical dashed line represents the approximated time of drop in the number of international flights. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

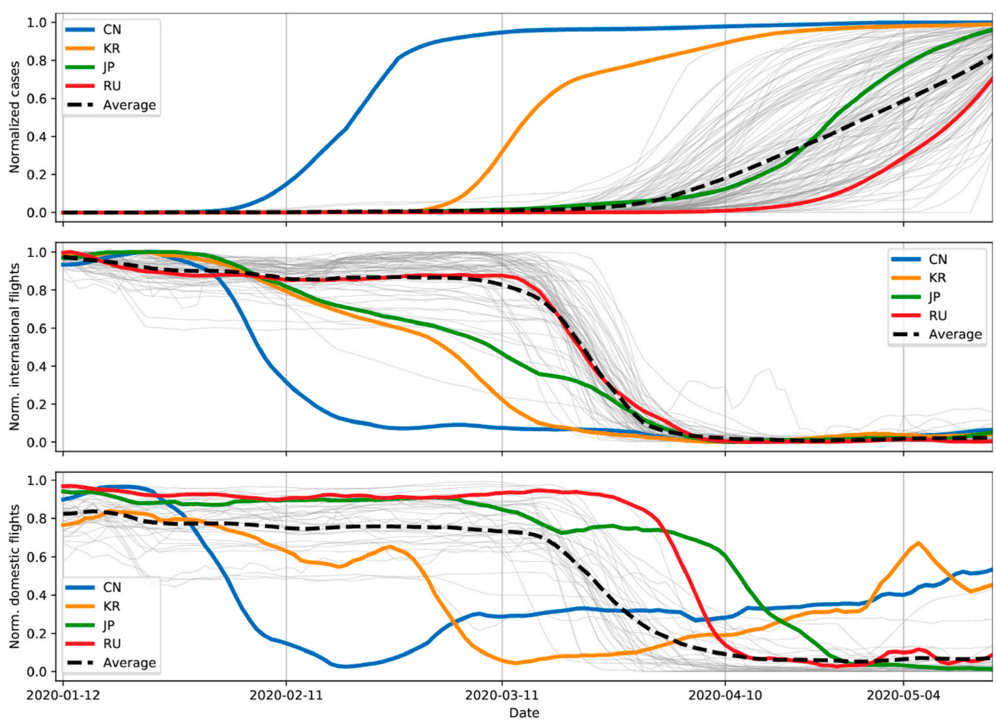

Fig. 5. The normalized number of infected cases for selected countries, the x-axis shows the timeline along the COVID-19 outbreak, while the y-axis shows the normalized number of infected cases, the normalized number of international flights, and the normalized number of domestic flights, ranging from 0.0 (minimum) to 1.0 (maximum). The light-grey curves denote the results of all remaining countries.

the number of countries being connected with at least one direct flight). One can distinguish two possible extremes in such experiments. First, the so-called diversity reduction, in which the country attempts to remove the degree significantly; which means that the number of destination countries served by airlines is reduced. Second, the so-called capacity reduction, in which the countries keep most of their destinations alive, while reducing the frequency of connections significantly. Fig. 7 presents an analysis of the air transport lock-down strategy of individual countries. We plot the curves for the normalized degree over time (0.0 = minimum degree of a country in the period, 1.0 = maximum degree of a country in the period) against the normalized number of international flights. While there is no explicit temporal information in this chart, the countries, in general, move from the upper left (large degree, large number of flights) to the lower right (small degree, small number of flights). The chart reveals that both extremes, diversity reduction and capacity reduction, are present in the response to COVID-19. For instance, Japan, after a short period of fluctuation, decided to carefully reduce the number of daily flights, while maintaining a high degree of diversity; i.e., the fraction of flights was reduced by almost 60%, but 80% of the destination were still served; which means that capacity (or frequency) was the focus of the lock down. An example for a country towards the other extreme is Panama, which rather chose to cut all flights completely, sharply reducing its degree right from the start.

Fig. 8 further pushes the envelope on answering the question whether the reaction of air transportation system was synchronized with the spread of the pandemic. For each country, we plot the day of the first 100 reported COVID-19 cases (x-axis) against the first day with more than 80% reductions in the number of international flights for a country. The color encodes the continent of a country. The two diagonal lines represent the perfect correlation between both indicators (black) and a 14-day pre-emptive flight reduction baseline, in which several countries have limited their air traffic 14 days before the outbreak of the first 100

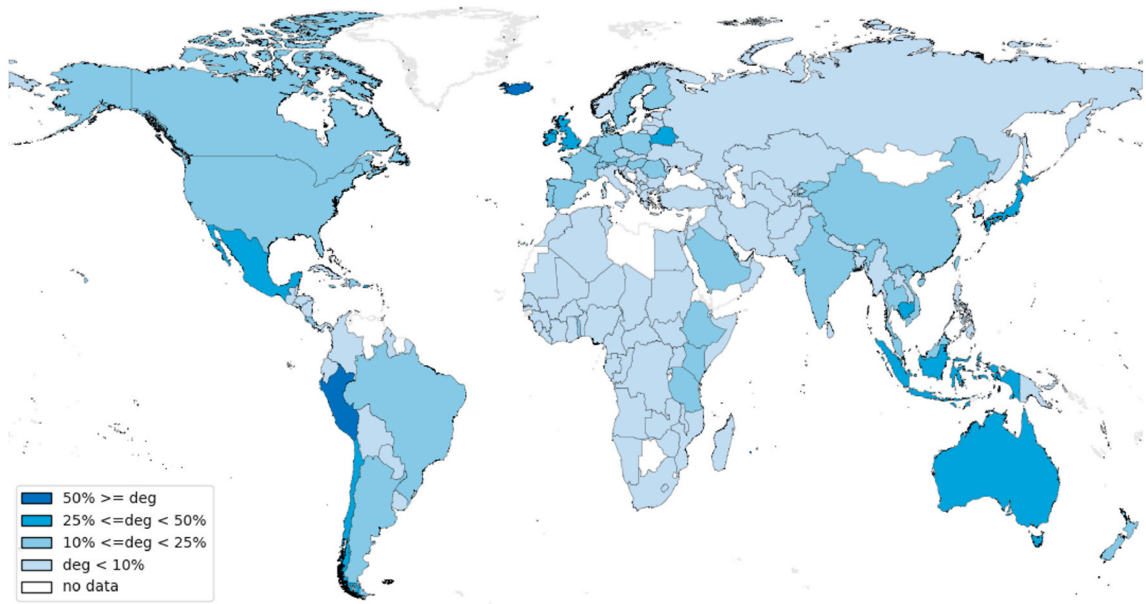

Fig. 6. Spatial distribution of countries with evolving connectivity patterns during the COVID-19 pandemic. Darker colors indicate less connectivity losses despite of the implementation of control measures all over the world. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

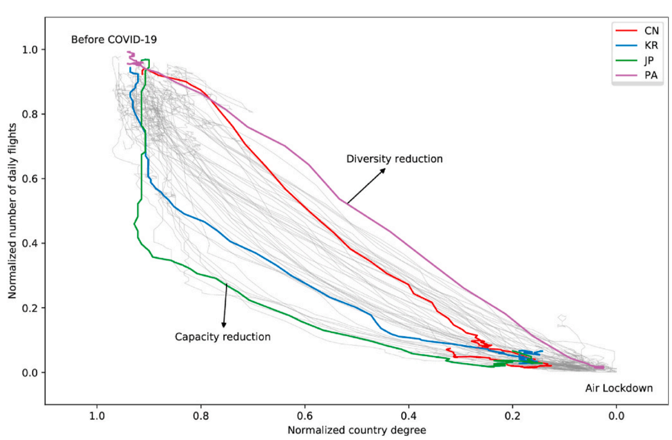

Fig. 7. The normalized degree (the number of flight connections with other countries) of a country versus the normalized number of international flights, where 0.0 denotes minimum and 1.0 denotes maximum after normalization. Four countries with representative patterns are highlighted: China, South Korea, Japan, and Panama. Two extremes of actions taken by different countries can be observed: Capacity reduction (represented by the green curve) and diversity reduction (represented by the purple curve). The light-grey curves denote the results of all remaining countries. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

cases (purple). Ideally, countries should be found towards the lower right of the purple diagonal line, if countries reacted early enough. Most of the countries, on the other hand, are located towards the upper-left, which means that the significant flight reduction happened much later than reaching the first 100 domestic COVID-19 cases (we analyze the sensitivity of the number of cases below). Moreover, for the few countries located towards the lower-right, their timely flight reductions had all occurred after March 11, the date when WHO declared the disease to be a pandemic. In fact, the majority of these counties made the decision after April 10. This suggests some international learning has taken place at the country/airlines level.

Given that distinguishing impacts of COVID-19 on the international market and the domestic market, we further examine the reactions of airlines on the domestic flights during the COVID-19 spread in Fig. 9. The day of the first 100 reported cases and the first day with only less than 20% domestic flights connection remaining are compared and contrasted. While the general flight reduction decision is consistent with the case of the international flights in Fig. 8, the actions of airlines concerning domestic flight operations are further delayed than those for international flight operations, this can be observed from the scatter plots that most data points appear above the black dashed diagonal line. Moreover, the number of countries taking actions on domestic flights is much less than those for international flights. This might be one indication that the deployment of cutting down international flights is more effective, and thus more widely implemented than reducing domestic flights, in addition to other anti-contagion measures, such as hygiene, social distancing, and home quarantine (Kraemer et al., 2020). It is interesting to note how UA appears below the purple dashed line; the reason is that UA has a very small number of domestic flights, since the country's transportation does not depend much on domestic flights (given it's spatial scale). Fig. 10 takes this analysis further, by presenting the number of reported, domestic cases by country, on the first day the international flights were reduced down to 20%. It can be seen that those countries with a large total number of infections are also countries which had already a large number of cases reported; accordingly, one can conclude that from the analysis in this study, the measures might have been taken too late.

4. Concluding remarks

4.1. Main results

This study has investigated the degree of synchronization between air transport connectivity and the number of confirmed COVID-19 cases on a worldwide scale, with countries (governments) as individual decision makers. To the best of our knowledge, this study is the first to provide an analysis on the degree of synchronization between air transport connectivity and COVID-19 cases, using recent global air traffic data. We investigated the two-way relationships between air transportation and COVID-19. The evolving dynamics of the synchronization relationships among three major criteria are reported: The

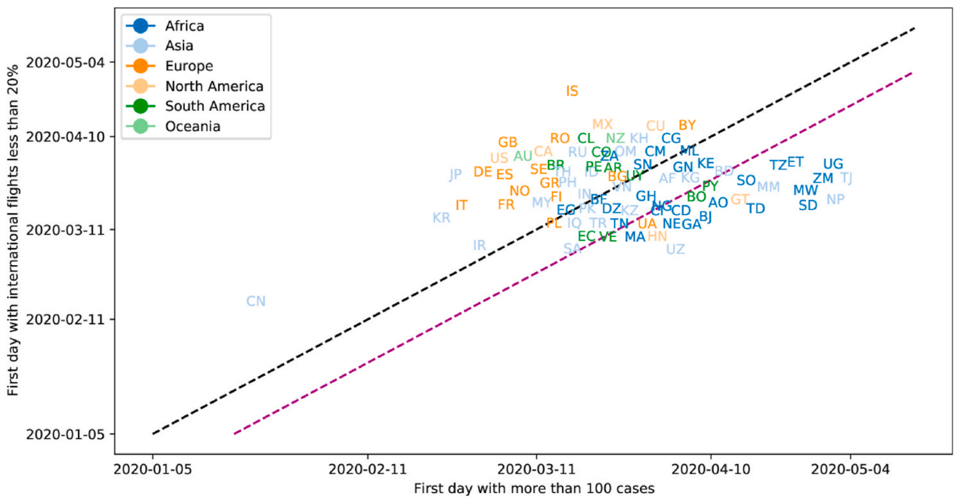

Fig. 8. Scatter plots for the day of the first 100 confirmed cases versus the first day with more than 80% reductions in the number of international flights for different countries. Countries from different geographical locations are denoted with different colors. The black dashed diagonal line represents a perfect correlation between the occurrence of these two events; while the purple dashed diagonal line represents a 14-day pre-emptive flight reduction reference. Only data for countries with more than 10 international flights per day are shown; 90 countries matched the selection criterion. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

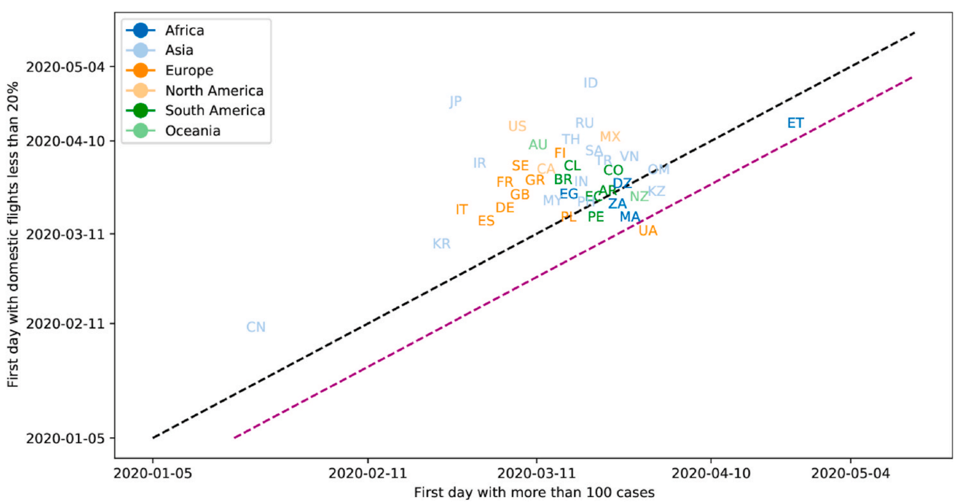

Fig. 9. Scatter plots for the day of the first 100 reported cases versus the first day with more than 80% reductions in the number of domestic flights for different countries. Countries from different geographical locations are denoted with different colors. The black dashed diagonal line represents a perfect correlation between the occurrence of these two events; while the purple dashed diagonal line represents a 14-day pre-emptive flight reduction reference. Only data for countries with more than 10 domestic flights per day are shown; 42 countries matched the selection criterion. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

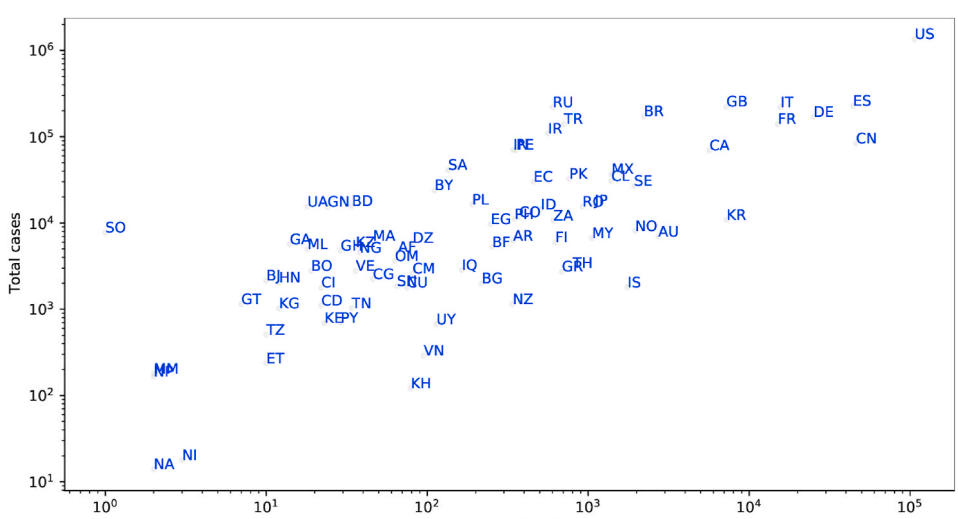

Fig. 10. Total confirmed cases in each country plotted against the number of confirmed cases on the first day the number of international flights was reduced down to 20% or below.

number of confirmed cases, the number of international flights, and the number of domestic flights for several major countries. Our study leads to a few key insights, which are listed below:

1. We observed that all countries reveal a two-stage pattern regarding the growth of COVID-19 infected cases: While the initial growth was towards a few hundred infections, within a few weeks the magnitude of infections quickly escalated to tens of thousands in an extremely short period of time.
2. Perhaps more strikingly, we found that almost all countries probably reacted simply too late in their decision to cut down flights, despite it being known for years that air transportation is crucial to understand the evolution of a pandemic.
3. We applied a widely used complex network centrality metric, the degree centrality, which measures the number of direct connections a country has to the international country network. Spatial distribution of countries with evolving connectivity patterns during the COVID-19 pandemic showed that the majority of countries have lately but significantly reduced the number of flight connections; many of these countries below 25%. A few countries have maintained a high degree of connectivity such as Mexico, Peru, Belarus, and Iceland.
4. We observed two extremes of actions taken by different countries/airlines: Diversity reduction and capacity reduction. While the former strategy attempts to reduce the connectivity intensity of a country, i.e., the number of countries served by airlines; the latter strategy intends to reduce the frequency of connections, while keeping most of their connections alive.
5. We also found that the reactions of airlines on the international flight operations and domestic flight operations are different, due to the distinguishing impacts of COVID-19 on these two markets. While the general flight reduction decision is consistent for airlines, the actions on domestic flights are even more delayed than those for international flights. This can probably be explained by the substantial effectiveness of cutting down international flights as one of the widely implemented anti-contagion policies.

4.2. Policy implications

A striking result of our investigation is that almost all countries probably reacted simply too late in their decision to cut down flights. As a result, the best strategic time window to implement control measures for the containment of COVID-19 is missed because of the delayed reactions from the governments (and airlines). Flight lock-down measures worked best before the virus started to spread inside a country, as per our finding of the two-stage pattern, which is an important policy lesson in the prevention of future pandemics. This also points to the critical role of international organizations, namely, WHO, ICAO, and IATA, in having a system to ensure earlier warnings and restrictions, and more generally, for better coordination and regulation. This system needs to anticipate that each individual country has, understandably, an incentive to maintain air transport connectivity, since it plays an important role in the citizens' mobility and the country's economic activities.

Relatedly, each country should also anticipate that airlines can have private incentives to maintain their flights during the early stage of an epidemic, in its policy formulation. For example, it has been reported that some airlines were flying (essentially) empty aircraft, in order to not lose their slots at slot-constrained airports. An earlier suspension of such slot policies should be implemented. Furthermore, the early flight reduction policy may be further combined with other regulatory restrictions. For instance, if a threshold number of people on board a flight test positive for COVID-19 after arriving in a country, the air carrier will be banned from flying that route for a certain period of time. This policy would incentivize airlines to ensure that every flight – before, during, and after – is as safe as can be.

4.3. Directions for further research

The paper has also raised several avenues for future research. First, we have analyzed the actual number of flights. This number does not contain any information on the load factor. In addition to the issue of slot policies mentioned above, some airlines were performing off-schedule flights for conducting take-home missions of passengers stranded in remote places; even into times when travel bans were active. The take-home operations often had a load factor close to 100%. Thus, the results of our study should be understood as a first step towards addressing the problem of synchronization. Nevertheless, the operations of these aircraft on their own, even if they were not fully loaded, put the crews and therefore the destination countries at high risk. In addition, the cost incurred by operating empty flights (just for keeping slots) are tremendous.

Second, it has been reported that some carries have used their passenger aircraft for cargo transportation during some phases of the pandemic, in order to increase revenue. It is difficult to obtain such operational data from airlines directly; yet, it is a very interesting direction for future work to analyze these operations and their effect.

Third, our investigation showed that countries had maintained varying degrees of their air transport connectivity in the response to COVID-19, and that both extremes of actions (namely, diversity reduction and capacity reduction) had been deployed by different countries. We see using econometric regression analysis (based on GDP and other indicators) to explain how these different strategies of individual countries impact their COVID-19 cases as a natural and important extension.

Finally, future research could look at passenger behavior from the demand side: How does travel bans and mobility restrictions change the behavior of passengers, and thus the demand of air transportation systems, which would ultimately influence airlines' operations. Because of different business models, reactions at specific airline levels, in particular, traditional major airlines and newly emerged low-cost carriers, could be compared and contrasted, in order to recommend appropriate reaction strategies. Given limited airport slot resources and the motivation to minimize losses due to flight cancellations, it would also be interesting to look at the interplay between the operations of passenger flights and cargo flights for different airlines.

CRediT authorship contribution statement

Xiaoqian Sun: Conceptualization, Methodology, Writing – original draft. **Sebastian Wandelt:** Data curation, Software, Visualization, Writing – review & editing. **Anming Zhang:** Conceptualization, Validation, Writing – review & editing.

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References

Balcan, D., Gonçalves, B., Hu, H., Ramasco, J.J., Colizza, V., Vespignani, A., 2010. Modeling the spatial spread of infectious diseases: the GLobal Epidemic and Mobility computational model. Journal of Computational Science 1 (3), 132–145.

Beck, M.J., Hensher, D.A., 2020. Insights into the impact of covid-19 on household travel and activities in Australia – the early days of easing restrictions. Transport Pol. 99, 95–119.

Bogoch, I., et al., 2015. Assessment of the potential for international dissemination of Ebola virus via commercial air travel during the 2014 west African outbreak. Lancet 385 (9962), 29–35.

Brockmann, D., Helbing, D., 2013. The hidden geometry of complex, network-driven contagion phenomena. Science 342, 1337.

Chen, L.H., Freedman, D.O., Visser, L.G., 2020. COVID-19 immunity passport to ease travel restrictions? J. Trav. Med. 27 (5).

Cheung, T.K., Wong, C.W., Zhang, A., 2020. The evolution of aviation network: global airport connectivity index 2006–2016. Transport. Res. E Logist. Transport. Rev. 133, 101826.
Chinazzi, M., et al., 2020. The effect of travel restrictions on the spread of the 2019 novel coronavirus (covid-19) outbreak. Science 368 (6489), 395–400.
Christidis, P., Christodoulou, A., 2020. The predictive capacity of air travel patterns during the global spread of the COVID-19 pandemic: risk, uncertainty and randomness. Int. J. Environ. Res. Publ. Health 17, 3356.
Coelho, M.T., Rodrigues, J.F., Medina, A., Scalco, P., Terribile, L., Vilela, B., Diniz-Filho, J.A., Dobrovolski, R., 2020. Global expansion of COVID-19 pandemic is driven by population size and airport connections. PeerJ 8 e9708.
Colizza, V., Barrat, A., Barthélemy, M., Vespignani, A., 2006. The role of the airline transportation network in the prediction and predictability of global epidemics. Proc. Natl. Acad. Sci. Unit. States Am. 103 (7), 2015–2020.
Gilbert, M., et al., 2020. Preparedness and vulnerability of African countries against importations of COVID-19: a modelling study. Lancet 395 (10227), 871–877.
Gillen, D., Morrison, W.G., 2005. Regulation, competition and network evolution in aviation. J. Air Transport. Manag. 11 (3), 161–174.
Gomez-Rios, D., Ramirez-Malule, D., Ramirez-Malule, H., 2020. The effect of uncontrolled travelers and social distancing on the spread of novel coronavirus disease (COVID-19) in Colombia. Trav. Med. Infect. Dis. 35, 101699.
Guan, D., et al., 2020. Global supply-chain effects of covid-19 control measures. Nature human behaviour.
Hossain, M.P., Junus, A., Zhu, X., Jia, P., Wen, T.-H., Pfeiffer, D., Yuan, H.-Y., 2020. The effects of border control and quarantine measures on the spread of COVID-19. Epidemics 32, 100397.
Hsiang, S., et al., 2020. The effect of large-scale anti-contagion policies on the covid-19 pandemic. Nature.
Huang, Z., Das, A., Qiu, Y., Tatem, A.J., 2012. Web-based GIS: the vector-borne disease airline importation risk (VBD-AIR) tool. Int. J. Health Geogr. 11 (33), 22892045.
Hwang, G.M., Mahoney, P.J., James, J.H., Lin, G.C., Berro, A.D., Keybl, M.A., Goedecke, D.M., Mathieu, J.J., Wilson, T., 2012. A model-based tool to predict the propagation of infectious disease via airports. Trav. Med. Infect. Dis. 10 (1), 32–42.
Khan, K., Arino, J., Hu, W., Raposo, P., Sears, J., Calderon, F., Heidebrecht, C., Macdonald, M., Liauw, J., Chan, A., Gardam, M., 2009. Spread of a novel influenza A (H1N1) virus via global airline transportation. N. Engl. J. Med. 361 (2), 212–214. PMID: 19564630.
Kraemer, M., et al., 2020. The effect of human mobility and control measures on the COVID-19 epidemic in China. Science 368 (6490).
Lee, D.S., Fahey, D.W., Forster, P.M., Newton, P.J., Wit, R.C., Lim, L.L., Owen, B., Sausen, R., 2009. Aviation and global climate change in the 21st century. Atmos. Environ. 43 (22–23), 3520–3537.
Li, J., Huang, C., Wang, Z., Yuan, B., Peng, F., 2020a. The airline transport regulation and development of public health crisis in megacities of China. Journal of Transport & Health 19, 100959.
Li, R., Pei, S., Song, B.C.Y., Zhang, T., Yang, W., Shaman, J., 2020b. Substantial undocumented infection facilitates the rapid dissemination of novel coronavirus (sars-cov2). Science 368 (6490), 489–493.
Nakamura, H., Managi, S., 2020. Airport risk of importation and exportation of the covid-19 pandemic. Transport Pol. 96, 40–47.
Nikolaou, P., Dimitriou, L., 2020. Identification of critical airports for controlling global infectious disease outbreaks: stress-tests focusing in Europe. J. Air Transport. Manag. 85, 101819.
Oum, T.H., Wang, K., 2020. Socially optimal lockdown and travel restrictions for fighting communicable virus including covid-19. Transport Pol. 96, 94–100.
Pigott, D., Golding, N., Mylne, A., et al., 2014. Mapping the Zoonotic Niche of Ebola Virus Disease in Africa. Elife.
Poletto, C., Boelle, P.-Y., Colizza, V., 2016. Risk of MERS importation and onward transmission: a systematic review and analysis of cases reported to WHO. BMC Infect. Dis. 16 (448), 731–753.
Suau-Sanchez, P., Voltes-Dorta, A., Cugueró-Escofet, N., 2020. An early assessment of the impact of covid-19 on air transport: just another crisis or the end of aviation as we know it? J. Transport Geogr. 86, 102749.
Sun, X., Wandelt, S., Zhang, A., 2020. How did COVID-19 impact air transportation? A first peek through the lens of complex networks. J. Air Transport. Manag. 89, 101928.
Tardivo, A., Martin, C., Zanuy, A., 2020. Covid-19 Impact in Transport, an Essay from the Railways' System Research Perspective.
The Atlantic, 2020. A century in the sky, 2020-06-16. https://www.theatlantic.com/sponsored/boeing-2015/a-century-in-the-sky/652/.
Wandelt, S., Sun, X., 2015. Evolution of the international air transportation country network from 2002 to 2013. Transport. Res. E Logist. Transport. Rev. 82, 55–78.
Wong, G., Liu, W., Liu, Y., Zhou, B., Bi, Y., Gao, G., 2015. MERS, SARS, and Ebola: the role of super-spreaders in infectious disease. Cell Host Microbe 18 (4), 398–401.
Zaki, A.M., van Boheemen, S., Bestebroer, T.M., Osterhaus, A.D., Fouchier, R.A., 2012. Isolation of a novel coronavirus from a man with pneumonia in Saudi arabia. N. Engl. J. Med. 367 (19), 1814–1820. PMID: 23075143.
Zhang, J., 2020. Transport Policy Making that Accounts for the Covid-19 and Future Public Health Threats: A Pass Approach. Transport Policy.
Zhang, Y., Zhang, A., Wang, J., 2020. Exploring the roles of high-speed train, air and coach services in the spread of COVID-19 in China. Transport Pol. 94, 34–42.