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Article

Assessing the Risk in Urban Public Transport for Epidemiologic Factors

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Abstract: Pandemics have presented new challenges for public transport organisers and operators. New diseases (e.g., influenza H1N1, severe acute respiratory syndrome—SARS, as well as, more recently, SARS-CoV-2) increase the need for new protection measures to prevent epidemic outbreaks in public transport infrastructure. The authors' goal is to present a set of actions in the area of public transport that are adjusted to different levels of epidemic development. The goal goes back to the following question: how can the highest possible level of passenger safety be ensured and the losses suffered by urban public transport companies kept as low as possible? The sets of pro-active measures for selected epidemic scenarios presented in the article may offer support to local authorities and public transport operators. In the next steps, it is important to develop and implement tools for public transport management to ensure safety and tackle epidemic hazards.

Keywords: epidemic; COVID-19; risk in transport

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1. Introduction

1.1. Literature Search

An important part of the analyses presented in the article is a comprehensive literature review. The literature review was aimed to provide a deep and exhaustive assessment of solutions adopted to reduce the risk of spreading the coronavirus SARS-CoV-2 in public transport. For each of the identified main topics, a unified literature search was performed to identify relevant studies, guidelines (based on reports), or web pages (ad hoc activities related to the COVID-19 pandemic). A standardized procedure was developed and applied to the article. Chapters were queried using sequences of keywords, and the results went through a process of selection. The literature search was carried out in the August 2020–May 2021 period. The selection of the papers included in our research was based on the following two sources: (1) our actual knowledge of the literature database we previously collected in our previous work on transport safety topics using Mendeley, and (2) use of the Scopus and Web of Science search engines for logical intersection of keywords and their combination, as follows: "spread of infectious disease" + "transport" + "COVID-19" + "prevention"; about 665 results were returned.

Obviously, it was impossible to include all of the journal papers returned by the search engine. Next, from the pre-selected works, the review papers and the works, which were focused on aspects not strictly related with our research (e.g.,: concerning private transport, regarding the spread of diseases by non-droplets routes, or focusing on SARS-CoV-2 origin, evolution and functional properties of viral proteins), were rejected. Therefore, the paper sample had to be narrowed even more.

As a result of the second selection, a group of 127 items was obtained. At this point, we decided to manually divide the selected work into three groups:

- Historical descriptions of epidemies breaking out before the appearance of the SARS-CoV-2 virus;

- Descriptions of transport risk analysis methods (all types of transport);
- Descriptions of the impact of transport on the transmission of infectious agents.

1.2. Background

Urban public transport is one of the key modes of transport. In many cities, a large number of people use trams, buses and underground every day. As cities grow and increase their populations, the constant development of urban public transport becomes necessary. Therefore, the design of a comprehensive and modern transport system to support inter-city and internal traffic is hugely challenging. This sets the context for the following issues [1–3]:

- Analysis of travel behaviour and management of demand integration within a group of cities;
- Design and management of agglomeration systems;
- Identification of risk and crisis management within an agglomeration system;
- Issues involved in sustainable urban development including the development of the transport system.

One of the policies designed to promote sustainable cities is to increase the share of urban public transport, making it a basic means of mobility for urban populations [4]. The operation of public transport, however, must be subjected to comprehensive performance and risk evaluation [5]. Considering the changes in the demographic structures of developed countries, access to urban transport for older people and people with reduced mobility should be one of the essential criteria for assessing mobility-related quality of life.

All types of transport—air [6–8], rail [9–11], water [12–14], and road transport [15–17] —have their own specific ways to manage risk. There is also a joint method to cover all of transport—TRANS-RISK [18–20]. In addition, there is a method for risk management in highway engineering [21,22].

The simplest definition of risk is the likelihood of a specific adverse consequence as a result of exposure to a hazard [21]. Risk management is based on three basic components, which must be defined: the probability of the risk, vulnerability to risk (related to resilience of, e.g., infrastructure when an undesired event occurs) and exposure (an equivalent homogeneous weighted value of people, infrastructure, different tangible assets that are affected by an undesirable event) [23,24].

Additionally, the bio-resilience of transport infrastructure is of growing concern, and should consider a diverse spectrum of threats, including endemic diseases, natural outbreaks as well as terrorism attacks. Currently, the coronavirus disease, referred to as COVID-19, has a strong impact on public transport and requires a robust and timely response. Global epidemics such as COVID-19 have a significant impact on tourism, transport, economy and energy demand [25–27].

The pandemic has set new challenges for public transport organisers and operators. New diseases (e.g., influenza H1N1, severe acute respiratory syndrome—SARS, as well as, more recently, SARS-CoV-2) increase the need for new protection measures to prevent both epidemic outbreaks and bioterror attacks in public transport infrastructure.

In the first stage of the epidemic, the number of passengers in countries hit by COVID-19 dropped dramatically, a consequence of heavy restrictions on movement of people and conducting business [27–30]. Many of the measures were introduced hastily and without preparation, all because procedures to handle epidemic hazards were simply not there. As a result, the measures were not very effective or overly restrictive. A frequent problem was that often the new regulations were not analysed for their consequences or risk. It was soon obvious that maintaining public transport restrictions long-term was not a viable option.

At present, the spread of the epidemic is slowing in many countries, travel restrictions are being eased and sectors of the economy are gradually resuming activity. The return to "normal" levels of service is gradual and transport companies are facing a dilemma: with social distancing rules still in place, vehicle capacities are significantly reduced. To make up for the restrictions, companies should increase the frequency of services as well as implement proper cleaning and disinfection. The above factors increase the costs, while revenues are expected to fall due to the limited amount of tickets sold. As a result, there is a concern: can public transport companies go back to the original number of passengers from before the pandemic? The transport policy must be revised at the national, regional, local (urban) and operator level.

1.3. Epidemic Threats

Throughout history, natural outbreaks of infectious diseases have challenged public health and safety, shaping human evolution, demography and migrations, trade and travel, economy and politics at both the national and international levels. The scale and spread of these challenges increased dramatically in agrarian communities, due to the more frequent person-to-person and human-to-animals contact. A wide range of microorganisms are considered as pathogens. Among them, infectious agents have been classified into five major types: viruses, bacteria, fungi, protozoa and helminths, with newly recognized prions as an additional class.

To reduce the burden of infectious diseases, different technologies and therapies have been used worldwide, such as: development of health systems (diagnostics, therapeutics, vaccination, antibiotics, medical practices, etc.) and improvements in sanitation (hygiene, access to clean water, and central systems for wastewater treatment). While mortality from infectious diseases is currently reported as declined, humankind is confronted with an ever-increasing number of emerging or re-emerging infectious agents that can cause pandemics. It is suggested that several factors underlie their emergence, including: urbanization, increasing population, connectivity and migration, deforestation and change in agricultural practices. Lifestyle diseases (e.g., obesity, hypertension, diabetes mellitus, allergic and auto-immune diseases) are also crucial in this process.

On the other hand, the expectations of an effective control of infectious diseases have increased. Thus, modern medicine is focused (I) on developing methods for rapid identification of pathogens, (II) determining an effective therapy in response to the genetic changes in pathogen populations, and (III) mitigating pandemics' driving force of transmission.

Recently, viral diseases have gained the most attention; however, their devastating consequences have been known since ancient times. The evidence of smallpox (caused by variola virus) was found in mummies of pharaoh Ramses V (1149_1145 BC) [31], a victim of poliovirus (poliomyelitis disease) was recorded in a stele of ancient Egypt, while Greek writings dated to 412 BC described an influenza outbreak. In recent history, the most severe influenza pandemic, called Spanish flu (H1N1 virus), infected over a quarter of the world's population (about 500 million people), and resulted in some 30 million to 100 million deaths (in comparison during the two World Wars roughly about 77 million people were killed).

Currently, variants of existing viruses (called re-emerging viruses) that cause serious epidemics (e.g., swine- and avian -origin influenza pandemic), together with newly emerging viruses, have become a global concern: HIV, severe acute respiratory syndrome (SARS, SARS-CoV), and Middle East respiratory syndrome (MERS-CoV), and haemorrhagic fever viruses such as Lassa, Ebola, and others.

In most cases, outbreaks of newly emerging viruses are explained by expansion of the human habitat, which has increased human-wild animals contacts. Crossing the species barrier to infect another species is not achieved easily, and it is still unclear when, where and how pathogens such as human immunodeficiency virus (HIV) or severe acute respiratory syndrome (SARS) have crossed the barriers of their natural hosts. In most cases, however, the direct contact of humans with the animals, their excreta, feathers, or meat are regarded as vectors of transmission. This may be exemplified by animal influenza, which has crossed the animal–animal or animal–human barrier in area where birds, pigs, and humans live close together. Currently, the majority of recently emerging infectious diseases have a wild animal origin, and viral disease spillover is probably vastly underestimated. If the species barrier is traversed and viral agents from animal reservoirs enter the human population, they can further undergo human-to-human transmission.

There are, however, many pathways of how viral particles can leave/enter the host body and have interactions between infective and healthy individuals (Figure 1). This knowledge is crucial to control the spreading mechanisms and support humanity's well-being. Additionally, the response and capacity of health-systems at local and national level highly contributes to the morbidity (and even mortality) rates of viral infections. In the prevention and control of infectious diseases, vaccination is a highly effective tool. Thus, in many countries, public health authorities have developed strategies for both mandatory and preventative vaccination and effectively share the information about infectious disease transmission and health threat, which are accelerated by the current lifestyle.

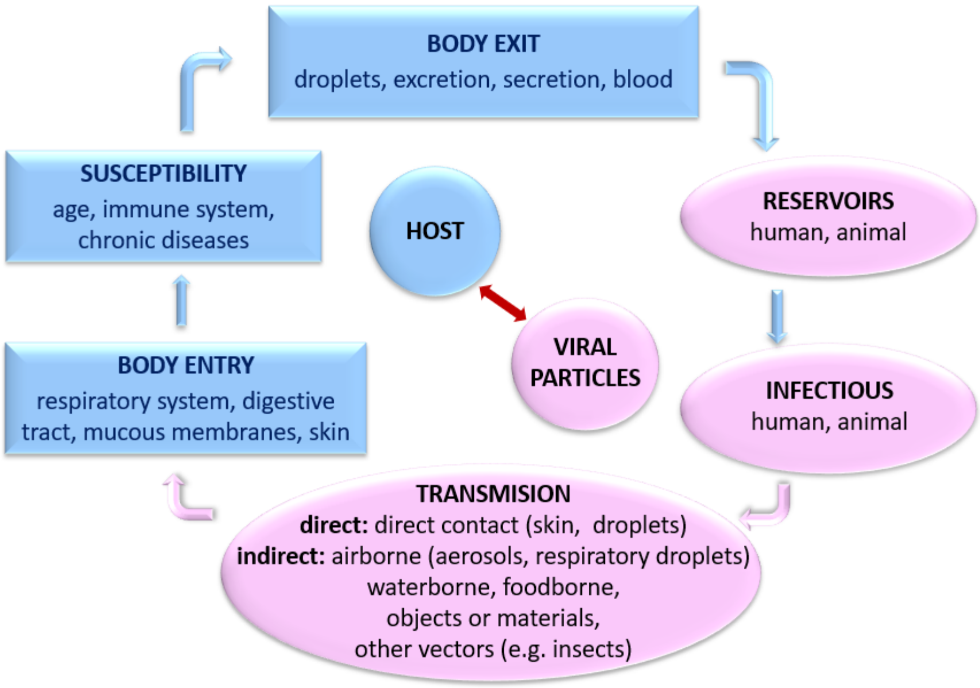

Figure 1. Pathways of viral particles and interactions between host body and environmental niches.

The classic epidemic model [32] is used to model epidemics where a typical subject first becomes susceptible, then falls ill and, after a short infectious period, builds a lasting immunity. It is called the SIR model (susceptible—infected—removed). The authors of [33] presented a model of an epidemic where people from a population fall ill and spread the infection as they move between two regions. The model is based on the epidemic model SIS (susceptible—infected—susceptible) which describes how an infectious disease spreads in a population of a specific size. In [34], the SEIR model was applied to simulate COVID-19. In SEIR, the total (beginning) population N0 is divided into four classes: susceptible S(t), exposed E(t), infected which infects I(t) and recovered R(t), where t is a time variable. In recent years, the consequences of an epidemic are modelled using "Framework for Reconstructing Epidemic Dynamics" FRED models [35]. They are publicly available open-source platforms which build on previously developed epidemic models. FRED simulates the development of an epidemic using data of a regional population, including land use, age and household income and the network of contacts in a household, school and workplace.

Key to studying the dynamics of infectious diseases globally is understanding human mobility and developing qualitative models and quantitative theories. Mobility over long distances is responsible today for the fast geographic spread of infectious diseases. Multiscale human mobility networks exhibit two prominent features: (1) Networks feature strong heterogeneity, and traffic flows and size of population range in multiple orders of magnitude. (2) Although the interaction magnitude in terms of traffic intensities decreases with distance, the observed power-laws indicate that long range interactions play a significant role in spatial disease dynamics [36]. More effective actions to stop the spread of an epidemic are possible thanks to new technologies such as mobile telephony and GPS [37]. Exact tracing of people's movements in real time helps to identify the contacts of infected persons.

1.4. Epidemics in Transport

Modern economic activities cannot be sustained without continuous travel and supply chains, which are also the main factors behind the spread of infectious diseases. It is obvious that in large and densely populated cities, with overcrowded transport hubs and associated infrastructure, inadequate ventilation may increase the transmission of infectious diseases. The explanation is the link to the reproduction number or R0, first introduced in the field of demography as a people reproduction measure [38], but currently used as a fundamental metric for studying the infectious disease dynamic [39]. The basic conceptual framework defines R0 as the number of secondary cases one case would produce in a completely susceptible population [40] and is usually calculated as a function of three main factors: (I) duration of recovery—the time it takes for an infected person to recover; (II) probability of transmission—the likelihood of infection per contact between a susceptible and infected person (or vector); and (III) the contact rate—the contact among individuals. The reproduction numbers (R0) of major viral infectious diseases are given in Table 1. To better describe how widely and quickly infectious diseases can be spread, additional parameters are usually added, e.g.,: the fraction of susceptible people in the population (e.g., survived infection or been vaccinated), population density (e.g., rural vs. urban), demographic trends (young vs. elderly), social organization (e.g., integrated vs. segregated), human social behaviour and seasonality.

For years, scientists have been studying the links between epidemics and transport. Research results [41] show that a transport-related infection affects the number of infections and duration of the epidemic as the disease becomes more endemic because of movements between two cities. Studies [42,43] show that when an infectious disease is being transferred from one region to another via transport, the set endemic state is globally asymptotically stable, regardless of trip duration, if the basic reproductive number $R0 > 1$. Studies [44] have demonstrated the effects of passenger transport on the spread of epidemics if $R0 > 1$. In [45], it was shown that the transport-related spread of a disease may cause an endemic disease, even if all regions isolated from the disease were free from that disease. Studies show that higher transport efficiency and better sanitary conditions and ventilation in public transport reduce the likelihood of an epidemic. Furthermore, that likelihood is lower if people are discouraged from taking non-essential trips during an epidemic [46]. To study how an epidemic spreads, detailed data were used regarding behaviour within a selected population [47]. Models were developed for Mexico City, which showed how population behaviour changed during the H1N1 epidemic and how that behaviour was influenced by government recommendations. The authors of [48] showed differences between how the Ebola virus epidemic evolved in developed and developing countries and how it was spread via air passenger transport. Some of the studies look at the effects of selected types of public transport on epidemic spread. An analysis of New York helped to estimate that if a pandemic were to break out in the city, the subway's share in overall transmission would be about 5% [49]. Examples of calculated reproduction numbers (R0) of major viral infectious diseases are shown in Table 1.

Table 1. Examples of calculated reproduction numbers (R0) of major viral infectious diseases.

Disease	Transmission	R0	Source
Measles	Aerosol	12–18	[50]
Chickenpox	Aerosol	3.7–5.0	[51]
Smallpox	Respiratory droplets	3.5–6	[52]
Influenza seasonal and pandemic	Respiratory droplets	1.1–2.8	[53,54]
SARS-CoV	Respiratory droplets	0.19–1.08	[55]
SARS-CoV-2	Respiratory droplets	1.4–8.9	[56]
MERS	Respiratory droplets	0.3–0.8	[57]

All of the above put mass transport systems under suspicion of amplifying and accelerating the spread of airborne and droplet-borne diseases due to intensive person-to person and person-to-vector (contaminated air or objects) contact in usually enclosed spaces. This is of high importance since the number of passengers using public transport has increased at both the national and international levels.

1.5. COVID-19 in Transport

Due to the long incubation time as well as mild or asymptomatic disease symptoms, high levels of SARS-CoV transmission have been carried via the transport network. Examples of coronaviruses dissemination by transport are given in Table 2 The examined cased did not give a simple answer about coronaviruses transition, which may have occurred during the flight. However, the majority of the flight-associated outbreak could be attributed to transmission elsewhere. The relative risk of importation and exportation of COVID-19 clearly shows that not only China, Europe, the Middle East and East Asia, but also the U.S., Australia and countries in northeast Asia and Latin America, are subject to risk [58].

Ref. [59] studied 318 in-door outbreaks of SARS-CoV-2 in China, which infected 1245 individuals in 120 cities. The above study has confirmed that outbreaks occurred mainly in shared indoor space, the quality of which is highly influenced by ventilation rates. The required ventilation rates vary significantly, and equalled 3–9 L/s per person in shopping malls and 2–8 L/s per person in public buses, whereas a ventilation rate of 8 to 10 L/s is required for good indoor air quality. Nonetheless many public spaces, however crowded, are poorly ventilated, with CO_2 concentration reaching 3500 ppm. It is often connected with the design/operation of buildings, which are influenced by the need to achieve energy efficiency. If greater focus is put on costs than health, the indoor environment may suffer from reduced ventilation.

Zhao et al., 2020, examined the association between the load of domestic passengers who travelled by domestic trains, cars and flights from Wuhan to six selected major cities, including Beijing, Shanghai, Guangzhou, Shenzhen, Chengdu and Chongqing, and the number of COVID-19 cases confirmed in those cities. According to the obtained data from 16 December 2019 to 15 January 2020 a strong and significant association was found only between travel by train and the number of COVID-19 cases, whereas the associations with two other means of transportation failed to reach statistical significance [60]. The possibility of infection on trains was not discussed in this study. The authors of [61] also indicated the important role of public transportation in the spread of COVID-19. A significant and positive association was noted between the frequency of flights, trains and buses traveling from Wuhan and the daily as well as the cumulative numbers of COVID-19 cases in other cities [61], with progressively increased correlations for trains and buses. In [62], it was suggested that the outbreak of a pandemic in a large city lying in the centre of a country such as Wuhan can have devastating impacts on the whole nation and that the extreme measure to lock down the city might have been a correct move to reduce such an impact on other parts of China.

Table 2. Examples of coronaviruses spread by means of transport.

In-Flight and Post-Flight
February 2003 Boeing 777-300, from Hong Kong to Taipei, 90 min, 315 passengers and crew members, 74 (23%) were interviewed, besides one person with presymptomatic SARS (confirmed to be seropositive for SARS-CoV) onboard, no additional illness consistent with SARS was developed [63]
March 2003 Boeing 737-300, from Hong Kong to Beijing, 3 h, 120 passengers and crew members, 65 (56%) were interviewed, one of the passengers was asymptomatic on board (latter confirmed SARS), in 20 persons SARS was confirmed to have developed, and 2 other persons were given diagnoses of probable SARS [63]
January 2020 Boeing 787-9 (equipped with air handling systems), from Singapore to Hangzhou Xiaoshan in China, 5 h, 335 passengers and 11 crew members, seat occupancy 89%, all passengers were interviewed; COVID-19 developed in 16 persons with the overall attack rate at 4.8%; the attack rate was higher (13.76%) among passengers who had previously departed from Wuhan (15 COVID-19 cases per 109 persons) than among those who did not have a history of travel to Wuhan (1 COVID-19 cases per 226 persons, attack rate 0.44%) [64]
Ground Transport
Significant association between the load of passengers who travelled by domestic train from Wuhan and the number of COVID-19 cases reported in the destination cities [60]
Progressively increased correlations for trains and buses traveling from Wuhan and the daily/cumulative numbers of COVID-19 cases in destination cities was reported [61]
Cruise Ship
The British-registered Diamond Princess with 2666 passengers and 1045 crew members from 56 countries (1281 from Japan) was the first cruise ship with a reported major outbreak of COVID-19 on board, 700 people became infected, and 14 people died, the ship quarantined at Yokohama for about 1 month since 4 February 2020 [65]

Outbreaks of infectious diseases have also been challenging for the cruise ship sector, since people spend time close together with travellers from many countries. The Diamond Princess was the first cruise ship with a major outbreak of COVID-19 on board. Since then, at least 40 other cruise ships have been confirmed to carry COVID-19-positive passengers and were quarantined. Forced quarantines, the quality of life of the isolated passengers and crew members, and the uncertainty of employers and procedural control measures raise the question of ethical considerations and global justice. Procedures undertaken during events such as these should be re-evaluated and require an international response and global regulations.

It is important to realize that each new pandemic is unique and follows its own logic. Thus, public health professionals should not rely on past experiences, but also draw their own conclusions. New diseases (e.g., influenza H1N1, severe acute respiratory syndrome—SARS, as well as, more recently, SARS-CoV-2) raise the need for new protection measures to prevent both epidemic outbreaks and bioterror attacks in the public transport infrastructure. The development of bio-resilient transport infrastructure is a growing concern, in terms of both public health and biosecurity.

1.6. Reason and Goal of the Paper

A review of pandemic measures, especially those undertaken in the early stages in different countries and on different continents, shows that they were frequently chaotic. With no previous strategy available, actions had to be taken with no certainty as to their outcome. Materials collected by the authors suggest that the main problem was that the countries lacked preparedness to act reasonably based on scenarios of pandemic threats. As a result, the decisions were either to close access to public transport completely or to make it fully available. One of the reasons why public transport struggled with the situation was that it lacked preparedness and staff training. This is a very important aspect, which should be addressed when developing future strategies [66]. As a consequence, it is important to prepare a set of actions to match the particular scenarios of epidemic risk, especially because that threat is likely to grow, and many countries are still recording very high numbers of infections and deaths due to COVID-19. It is clear that while countries' local specificity and conditions must be considered, some fundamental principles should be prepared and implemented. The authors' goal is to present a set of actions in the area of public transport that are adjusted to different levels of epidemic development. The goal goes back to the following question: how can the highest possible level of passenger safety be ensured and the losses suffered by urban public transport companies kept as low as possible? To achieve this goal, a set of actions was prepared, which public transport companies must roll out based on risk management tools.

Energy consumption is a very important aspect linked to the decline in public transport in cities. Increasing levels of pollution, congestion on the roads and energy consumption in cities are becoming sensitive issues that could be mitigated by more efficient public transport systems and an increased share of urban travel by public transport [67]. The epidemic threat has reduced the share of public transport travel, and this reduction occurred drastically during national lockdowns. Subsequently, this share has slowly increased, but fears of the possibility of contracting the virus caused a permanent decrease in public transport use compared to the situation before the pandemic. The alternative is often the use of individual transport, which translates into an increase in energy consumption.

Studies in American, Canadian, Australian, European and Asian Cities show that energy consumption per person in private transport was more than 20 times higher than on public transport, and 2.3 times higher per passenger kilometer [68]. The approach, proposed by the authors, to the epidemic threat involves optimization of the operation of public transport according to different epidemic development scenarios, as well as the return of passengers following the epidemic. This will allow sustainable transport to be further developed and energy consumption to be decreased by reducing the share of individual transport.

2. Materials and Methods

2.1. Review of Public Transport Measures

The earliest signs of a new coronavirus were first recorded in the Chinese city of Wuhan. On 31 December 2019, the WHO reported a cluster of cases of pneumonia ([69]. All over China, in January 2020, inter-city passenger traffic (all forms of transport) fell by about 90% year on year, with cargo transport in February 2020 dropping by about 30% year on year [70]. While measures were taken, they were not able to stop the spread of the coronavirus. Pathogens were scattered over a large part of China by people travelling by train and plane [71]. As a result, the epidemic was quick to spread outside of China. The virus was carried to other countries primarily by air transport, used by thousands of people traveling daily, from China to the majority of countries worldwide.

In Europe, measures were launched to stop the spread of the coronavirus and slow the number of infections in the first half of March 2020. On 13 March, Italy imposed nationwide travel restrictions (using air, sea, rail and road transport) [72]. On 13 March, France also introduced far reaching travel restrictions [73]. On 15 March 2020, Poland closed its borders and suspended international air and rail transport [74]. On 24 March 2020, restrictions were placed on public transport [75]. At the same time, other European Union countries were introducing similar restrictions. India imposed restrictions on transport use in late March [76]. At the end of March 2020, some 2.6 billion people (i.e., 35% of the world's population) found themselves under lockdown, a measure imposed to reduce the further spread of the epidemic hazard [77].

2.2. Review of Strategies Designed to Tackle the COVID-19 Epidemic

Previous risk assessment methods and measures applied to public transport vehicles were not designed to deal with the dramatic development of the new coronavirus. While it was clear that seasonal epidemics of influenza were reinforced by infections in overcrowded public transport systems [78], studies also showed that when the situation is normal, the number of pathogens public transport passengers come into contact with is just a small fraction of overall contacts people are exposed to during their daily activities [79]. With the introduction of rigorous restrictions on human contact as a result of the coronavirus pandemic, the number of activities fell, making the transmission of infectious agents during trips a much bigger threat. Faced with the hazards involved in large groups of people moving within an enclosed space, i.e., means of public transport, local public transport authorities started to introduce temporary and experimental crisis management methods. The objective was to contain the main routes of transmission of infectious agents that are present in public transport:

- Contact between skin and infected material;
- Droplets;
- Inhalation.

Analysis of the responses undertaken by public transport authorities shows that there were five main strategies, as presented in Table 3.

Table 3. Public transport strategies adopted during the outbreak of the COVID-19 epidemic.

Strategy of Action	Characteristics
ST1. Preventative measures with no cases reported yet	Need to consider epidemiological hazards. No restrictions in accessing public transport but preventative measures are necessary, such as frequent vehicle disinfection. A continuous supply of personal protection equipment and disinfectants is required.
ST2. Recommendations for passengers and increased frequency of vehicle cleaning	The objective is to increase the safety of public transport users. This strategy should be applied when the epidemiological hazard is small. In this case, the majority of services are still open and population mobility drops just because of individual choices (90% of normal activity). The strategy reduces a small number of transport services to match reduced passenger flows.
ST3. Reduce the frequency of traffic or introduce functional restrictions on transport	The objective is to encourage people to change their transport patterns. This strategy should be applied for medium level epidemiological hazards if most workplaces continue to operate and people's economic activity continues to some extent. In these cases, there are no drastic falls of mobility (30–50% of normal value).
ST4. Transport system only covers essential travel for key workers	The objective is to ensure that the conurbation continues its basic functions. This strategy, when viewed with hindsight, should be considered appropriate if the epidemic hazard is serious. It should be applied when key parts of the economy continue to operate, but other people are encouraged to stay at home or work online. In this case, people's transport needs drop to 10–20% of normal activity.
ST5. Complete closure of transport system	This strategy, when viewed with hindsight and based on the experience from the other strategies, should be considered too restrictive if applied commonly. It may only be applied when the economy comes to an almost complete stop and people's transport use needs drop to nearly zero.

2.3. Changes in Transport Behaviour of Urban Populations in Selected Countries

Thanks to new technologies, it is possible to estimate the activity of public transport users and their daily behaviours. The analyses used open source data on Android mobile phone users [80] and behavioural data [81]. The data helped to describe changes in the typical behaviour of people living in selected locations which were the result of restrictions introduced to respond to threats of the SARS-CoV-2 pandemic. Appendix A presents detailed data for selected countries. China was first to introduce procedures designed to reduce the likelihood of an infection because the country was also the first to be affected by mass infections. The initial and most drastic measures included a complete suspension of public transport (ST5) in the hardest hit cities—Wuhan, Huaggang, Xiantao, Chibi and Lichuan—or making public transport available to key workers only (ST4). Tying into that was a complete or partial lockdown, during which trips fell significantly. Population activity was reduced to essential travel by key workers (medical personnel, food suppliers, city services, etc.). Population mobility fell by more than 90% year on year and major mobility changes continued all through April 2020 (which was when ST3 was introduced). Cities less affected by the epidemic saw less restrictive measures. Beijing introduced restrictive rules for cleaning and disinfecting public transport, with vehicles cleaned and disinfected up to several times a day or even after each service (typically, vehicles are cleaned once a day with disinfections taking place even less frequently). Because disinfection is time-consuming, innovative methods were tested using UV light or robots for spraying disinfectants. Drivers were equipped with gloves, masks and disinfectants. With schools and universities closed, student trips fell and new additional rules could be introduced:

- Only 50% of passenger capacity could be used;
- Seats next to an occupied seat could not be used;
- Seated travel only.

Because the capacity of urban means of public transport is the sum of seats and standing spaces, it is clear that the number of passengers was in fact restricted by more than the reported 50%. No overcrowding was recorded, however, because trips fell by as much as 90%.

South America introduced similar restrictions. While public transport continued to operate, it was to be used by essential workers only (ST4). Passengers should stay 1.5 m apart from one another and the driver. Other (less essential) underground stations were closed to force travellers who are not in essential jobs to not use transport (ST3). There is a very strong correlation between the restrictions and population mobility, as can be seen from the data charting new places of activity of mobile phone users. In mid-March 2020, traveller numbers fell by about 80%. This was in connection with fewer people traveling to their workplaces (a drop of about 75%) and more people staying home—a drop of 40%.

The US was not sufficiently quick in introducing restrictions or protective measures in public transport. The measures taken in March 2020 involved a reduced frequency of trains (ST3), which led to overcrowding [82]. This is because traveller numbers did not change as much as they did in China or Peru. They were late in introducing staff and passenger protection measures and reducing overcrowding during peak hours. As a result, in the transport system of New York alone, 123 employees died of coronavirus by mid-May 2020, with nearly 9000 employees contracting the coronavirus [83].

Europe featured a wide variety of public transport guidelines. Ukraine and Serbia suspended their public transport systems completely (ST4 or ST5) for some time (from March 2020), and it was not until the first half of May 2020 that they allowed passengers to use that transport again (ST2 or ST3) [84,85]. France, Germany, Poland and many other countries never banned public transport. However, certain restrictions were in place (ST2 or ST3):

- Keeping a distance between passengers—a range of solutions from banning standing or the use of seats next to an occupied seat, designating seats for passengers or marking zones on the floor to be used by a single passenger only, all the way to nationwide regulated vehicle capacities;
- Limiting the use of buttons by passengers (for example, by disusing stops per request), using central door opening systems, disactivating ticket machines, and introducing free travel;
- Contact was restricted between drivers and passengers by using physical cabin separation, stopping ticket sales, and having passengers use back doors;

- Having passengers wear mouth and nose masks and encouraging people to cover their eyes;
- Encouraging people to disinfect their hands;
- More frequent vehicle disinfections;
- Vehicles were regularly aired, and doors and windows were opened; air-conditioning was not used.

As a result, cases among public transport passengers and drivers were not reported to have increased compared to the rest of the population [86].

Sticking to the sanitary regime in Poland was problematic because nationwide vehicle capacity limits (ST3) meant that the transport system was unable to carry all passengers waiting to come on board. Under the restrictions, passenger numbers could only account for half of the seats. As a result, high-capacity trams that can carry up to 200 people were only allowed to take 14 after the introduction of the restrictions. This meant that the supply of places in trams dropped by 93% with passenger numbers not dropping that much—by about 60%. The nationwide recommendations were dropped fairly quickly, leaving more space for local public transport authorities to make decisions. At present, strategy (ST2) is in place.

In Germany, however, which saw similar drops in travel as in Poland, the regulations did not introduce such restrictive rules. Even in France, with the Paris region (Île-de-France) recording passenger reductions of 80%, passengers were allowed to stand while maintaining social distancing rules.

The United Kingdom was behind compared to other countries, with no early restrictions (initial lack of strategy), a move heavily criticised as potentially aiding the spread of the virus on overcrowded trains and buses. By mid-May 2020, the coronavirus caused the death of 33 employees of Transport for London, including 29 bus drivers [87]. The first measures taken included a reduced frequency of train services and closure of certain stations (ST3—partially). With no national lockdown in place, the result was significant overcrowding of public transport [88] even though trips fell significantly. It took a few months of travel in overcrowded trains and buses before, in June 2020, passengers were asked to wear mouth and nose coverings. In May 2020, the use of masks on public transport was encouraged by the government but not required. The UK was quite late in introducing other measures, which most of Europe already had in place. It was not until the end of June 2020 that public transport passenger limits were introduced (ST3—full). This makes the UK's policy very much an ad hoc action, with responses taken as the hazards emerged but no advanced plan.

From the start of the epidemic, Australia introduced rigorous rules for cleaning vehicles and ticket machines and card readers (ST2). A series of recommendations was issued regarding safety of travel:

- Planning trips outside peak hours to avoid overcrowding;
- Free travel outside peak hours to encourage travel planning even more.

Sydney launched a travel plan application which recommended walking or cycling for short trips. A campaign was run about personal hygiene and the need for passengers to stay apart at each stage of their journey. It was not until May 2020 that public transport passenger limits were introduced after urban trips rose again [89] (ST3).

India went into lockdown at the end of March, with (ST5) coming into force for transport. In May, the restrictions were eased when zones of epidemiological hazard were introduced. Lockdown continued within the containment zone. The red zone is the implementation of (ST4), orange zone is (ST3) and green zone is (ST2), but the number of buses was halved [76]. This shows that the measures matched the level of epidemic risk.

In Japan and South Korea, the work cultures are different from those in Europe. The Japanese were reluctant to move into working from home and, as a result, demand for transport services could not have dropped as much as it did in Europe. In most cities, public transport continued to operate fairly normally (ST2) [90]. The difference between Japan and South Korea and Europe is that in recent years the people of Asian cities have gone through a few epidemics and use higher safety standards on a daily basis. For this reason, wearing mouth and nose masks is normal in overcrowded spaces. Additional safety measures were introduced to tackle the coronavirus, such as disinfection of passengers' hands, stations and vehicles.

The use of public transport in relation to daily cases in particular countries shows differences in how the epidemic develops and how the populations behave. In recent weeks, the US and India have seen an increasingly high number of new daily cases of COVID-19 and a continuously low public transport uptake. While there has been almost no change in the number of cases recorded in Poland, Germany and France in recent weeks, public transport trips keep growing and have practically gone back to pre-epidemic levels. Peru and the United Kingdom have recorded similar daily cases of COVID-19 in recent weeks, but public transport trips have increased very little.

If introduced early on, a well-thought-out strategy means that the risk of coronavirus transmission among public transport passengers is not higher (as shown in France, Japan, Korea, Poland and Germany). With no strategy, infections of staff may rise very quickly and lead to a loss of capacity to deliver basic transport services, as seen in the USA and the United Kingdom. In New York, when infections were at their highest (May 2020), as much as 41% of subway trains had to be cancelled due to staff calling in sick [91]. If they are too restrictive, however, strategies may cause a significant increase in the costs of public transport operation while ticket revenue falls sharply [92]. This may financially incapacitate the entire transport system. It is clear that the anticipation of population mobility and the immediate response to changing mobility are crucial.

2.4. Assessment of Transport-Related Epidemic Risks

People travel or commute daily for educational, business or personal reasons. In overcrowded public transportation hubs, frequent human–human or human–fomite contact facilitates the short- and long-distance spread of pathogens. In these conditions, droplets and/or air particles represent a major channel of epidemic propagation. Respiration activities, such as breathing, coughing and sneezing, can generate thousands of droplets. A single sneeze contains about 40,000 large droplets, mostly in the range of 0.3 to 100 µm in diameter [93–95]. Droplets which contain cellular fragments, particles of viruses, bacterial cells or fungal spores are usually described as bioaerosol.

The WHO makes a distinction between droplet transmission of infectious diseases and airborne transmission [96]. Airborne transmission usually refers to the presence of microbes within nuclei smaller than 5 µm in diameter, which can remain in the air for longer and can be transmitted over distances greater than 1 m. In the case of droplets, transmission of less than 2 m is usually reported. Larger droplets (>50 µm) are usually deposited on nearby objects, while smaller ones (5–10 µm) can be suspended in the air. Outside of the host body, respiratory viruses usually remain infectious for a period from several hours to several days [97].

On average, a person inhales approximately 10 m^3 of air per day. Particles of droplets >6 µm are deposited in the upper airway, while smaller ones can penetrate into the lower respiratory tract (to the lung), posing a high risk of infection [93,96]. In these conditions, the relative distance between the infected and exposed person is an important parameter. This topic was already studied in the 1930s [98] and 1940s [99]. To control the spread of disease, it is important to determine the range of droplet velocity. It was set as follows: for breathing—about 0.1 to 1 m/s (the spread distance is about 1 m); for speaking—2–10 m/s. The coughing droplet reaches 10–20 m/s and can be spread over more than 2 m [100]. Another crucial parameter is connected with the infectious dose, which for some airborne viruses (influenza) is usually very low [96].

Besides humans, bioaerosols may also be generated by other sources such as heating, ventilation and air conditioning (HVAC) systems as well as by cooling tower in hospitals [93]. Currently, HVAC systems are usually responsible for reducing or accelerating airborne disease transmission, because they help to control temperature, relative air humidity and air currents. Virus particles may be emitted into the indoor space by infected individuals and when they enter the return air system, they may be spread throughout a building by the HVAC system. Thus, a properly functioning and maintained HVAC system (or the lack thereof) is one of the most critical factors in the crowded, small indoor spaces of public transport hubs and transport vehicles [63,101–104].

In 2007, the WHO [105] released guidelines which, for the first time, demonstrated a growing recognition of ventilation systems (natural and artificial) in controlling the spread of infections. Proper and effective ventilation (exchanging the air in passenger cabins every three to four minutes), together with the filtration of recirculated air through high-efficiency filters (HEPA), is regarded as an effective tool for reducing the spread of airborne pathogens on airplanes [106,107]. However, if ventilation is non-operational or insufficient, the number of infectious agents in droplets increases and transmission becomes widespread, which was confirmed by, e.g., influenza outbreak [101,106,108]. In addition, Severe Acute Respiratory Syndrome (SARS) associated with coronavirus (SARS-CoV) was transmitted via droplets in aircraft; this was first reported in [63,109]. However, it was concluded that the risk of SARS-CoV transmission is not amplified onboard [109]. A link between ventilation effectiveness and indoor outbreaks of COVID-19 was reported by the authors of [59].

Furthermore, other viral pathogens, such as influenza [110] and measles [111], have been reported by travellers arriving by airplane. The authors of [112] suggested a link between the spread of influenza-like illnesses (ILI) and long-distance travel. In addition, public transport passengers (bus and tram) are more frequently exposed to respiratory viruses and may either develop diseases or acquire immunity against a range of respiratory diseases. When novel viruses appear in public transport, the risk of acquiring an acute respiratory infection may rise due to a lack of immunity among the general the population [113].

2.5. Risk and Action Scenarios

2.5.1. Transport Hazards

Safety can be defined as a "state in which hazards and conditions that lead to physical, psychological or material harm are controlled to ensure that individuals and communities stay in good health and well-being." That state does not only involve a lack of consequences but must also be perceived as providing protection from danger. As a result, it covers two dimensions. One is objective and assessed based on the extent of injury or real behavioural and environmental parameters (such as the number of road deaths recorded in a given area, the share of drunk drivers or the number of junction crashes). The other is subjective and assessed based on a perceived sense of danger (e.g., parents do not feel safe enough to allow their kids to walk to school because they will be crossing what they consider to be a dangerous street) [114].

Safety involves hazards and risks. A hazard may be defined as the possibility of an undesirable phenomenon occurring (such as a transport accident) leading to adverse consequences (financial, environmental, injury or death). The simplest definition of risk is the likelihood of a specific adverse consequence as a result of exposure to a hazard [115].

To further elaborate on these simple definitions, we can say that a "hazard" represents those elements which may influence the consequences. While they do not cause consequences themselves, they have the potential to cause harm. The potential may be released if additional factors emerge. In the case of "risk", this will be the possibility of losing something of value such as good health, life, property, the environment, etc. It is in fact the likelihood of an undesirable event which leads to harm.

It is important to differentiate between risk and hazard. Both terms are frequently used interchangeably despite some key differences [116]. Risk points to an expected harm while hazard identifies the expected cause of the harm [117]. Risk is the likelihood that an action or inaction may be hazardous to life, property or the environment. Hazard refers to an object, situation or physical surrounding which is hazardous to life, property or the environment. Risk is measurable because likelihood can be estimated. Hazard is impossible to measure. This shows that risk is the likelihood of hazards becoming activated and that we should use terms such as the risk of activating hazards or the risk of hazards.

Transport systems are designed and operated to ensure that people, goods and services can be moved efficiently and safely. Nevertheless, there are many hazards which interfere with how the systems operate or damage these systems. These hazards include extreme weather and earthquakes, which are very difficult to predict, manage or mitigate. Such undesirable events may seriously impair a transport network, increase costs and reduce safety. Transport system hazards also include transport accidents. They have a significant effect on the operation of transport and on the safety of its users. As presented in Section 1 of the article, epidemiological hazards are key to how transport operates. It has been demonstrated that in extreme cases (as regards public passenger transport) a possible consequence is a complete discontinuation of this type of transport globally, nationally, regionally or locally (city level). Systematic study, designed to identify, assess, classify and prevent hazards, is increasingly more important as the role of transport grows. Transport safety is considered a key factor because it affects people's lives and health. In addition, transport accidents have a negative effect on the environment [118]. Epidemiological hazards in transport constitute one type of hazard that may be controlled. It is important to use the right strategy for the right level of risk to health.

2.5.2. Transport Risk and How It Is Defined

Sadly, transport systems go hand in hand with hazards. Road, rail, air or water transport involves the risk of undesirable events with consequences ranging from insignificant (incidents) to serious (if there is a transport catastrophe). In the context of epidemiological hazards, this means an infected person staying in a vehicle, which may have no consequences or cause an outbreak.

The study of adverse transport events can be broadly divided into the analysis of transport hazards, vulnerability and risk. The main objective of hazard analysis is to identify threats to a transport system, its users and resources [118]. Transport hazards may occur at different scales of consequences, from a pedestrian walking into a pole in the middle of a pavement to a fire in a road tunnel. Vulnerability analysis focuses on variation in the susceptibility to loss from hazardous events. Vulnerability can be viewed as the inverse of resilience to threats. Risk analysis incorporates the likelihood of an event and its consequences with the events ranging from an incident or conflict to transport catastrophe with multiple deaths. For example, identifying the hazards of a road landslide would constitute an analysis of a transport hazard. The destruction or damage to the road will have varying consequences depending on its significance in the system and the economic consequences for the region. Analysis of how the magnitude of the landslide would change constitutes vulnerability analysis. In risk analysis, the likelihood of a landslide and its associated consequences is incorporated to identify potential landslides that represent unacceptable risk.

Risk management is a repetitive and formalised procedure which combines the phase of risk assessment and the phase of risk treatment. The objective of risk management is to optimise safety-related decisions and minimise the adverse consequences suffered by system users (e.g., transport system users). Figure 2 shows the stages of risk management [119].

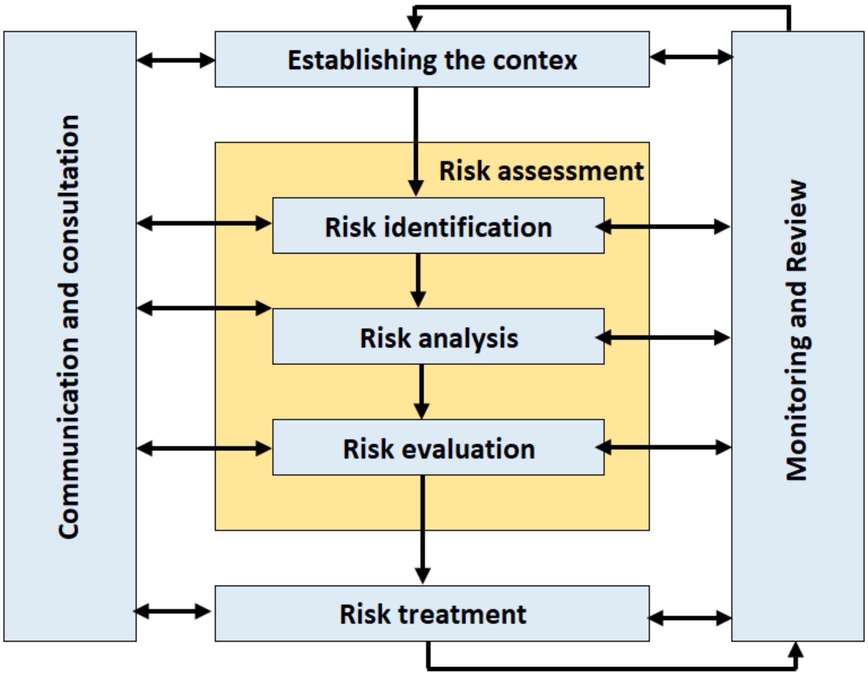

Figure 2. Stages of risk management.

Establishing the context is the early stage, which is designed to define the area of further work. Risk identification is when hazards are identified and the work presents the relevant methods. Risk analysis is a process which uses information to assess the level of risk. This helps to establish a hierarchy of risk during risk evaluation. One of the objectives of risk analysis is to separate less significant risks from those that require treatment quickly. During risk evaluation, risk assessed during risk analysis is assigned to pre-defined risk acceptability classes. Risk treatment is a set of tools, procedures or processes designed to change the potential level of risk when that level is unacceptable or leave it as it is if the level is acceptable. The risk matrix is a tool which supports risk treatment [120]. Table 4 gives an example in relation to epidemic risk.

Table 4. COVID-19 risk matrix for public transport with suggested strategies for specific risk levels.

RISK		Consequences of Infection			
		Insignificant	**Low**	**Serious**	**Catastrophic**
Probability of infection	frequent	medium (ST3)	medium (ST3)	high (ST4)	very high (ST5)
	likely	low (ST2)	medium (ST3)	high (ST4)	high (ST4)
	sporadic	slight (ST1)	low (ST2)	medium (ST3)	high (ST4)
	rare	slight (ST1)	slight (ST1)	low (ST2)	medium (ST3)

As regards the likelihood of an epidemic hazard, the levels are defined as follows:

- Rare—single cases of infection, full control over potentially infected people;
- Sporadic—a few cases of infection, over a small area (city), continued full control over potentially infected people;
- Likely—numerous cases of infection, over a large area (region), partial loss of control over infected people;
- Frequent—mass infections, whole country, significant loss of control over potentially infected people.

As regards the consequences of an epidemic hazard, the levels are defined as follows:

- Insignificant—using public transport leads to occasional infections, no outbreaks;
- Low—using public transport leads to occasional outbreaks in a city;
- Serious—using public transport leads to local outbreaks in a region;

- Catastrophic—using public transport leads to numerous outbreaks, across different regions, which eventually leads to loss of control over infected people.

Strategies ST1–ST5, matching the risk levels, are adopted based on Section 2. These assumptions help to develop scenarios for taking the necessary action to limit the risk of spreading the disease when using public transport.

2.5.3. Preparedness and Response in Epidemic Development Scenarios

The first International Health Regulations were adopted in 1969, mainly to prevent and protect public health against quarantinable diseases (yellow fever, plague, cholera and smallpox) and to introduce reliable and effective preparedness and response measures. The above regulations were amended several times due to growing international travel and trade, and the emergence/re-emergence of the global spread of diseases. The last amendment in 2005 (in force since 2007) was a response to the first global public health emergency caused by the first SARS outbreak in 2003 [121].

Epidemiological analysis and forecasting rely on accurate and timely data, which is especially critical at the early stage of epidemiologic investigations. Thus, the WHO has established a global surveillance system that gathers standardized data connected with infectious disease outbreaks, mainly of individual confirmed infectious cases, although other information such as travel and trade volume or migration patterns, etc., is also collected. Thus, in 2019, after early epidemiological evidence that a new coronavirus is likely to occur, models of transmission through droplets, personal contact, and contaminated objects (fomites) were suggested (due, among other reasons, to the similarity to previous outbreaks of MERS-CoV and SARS-CoV) together with the epidemic development scenario. The WHO surveillance system, as a constantly updated dataset, has also been used to refine recommendations for surveillance and case definitions, which helps to understand the spread and spectrum of the SARS-CoV2 virus and its impact on the community. Accurate and real-time data on the number of total infected cases, daily new cases, active and critical cases, deaths and recovered cases are essential in establishing integrated operational models for implementing countermeasures and introducing restrictions—defined as alerts (for details, see Table 5). The alert system is based on risk indicators and community measures, according to the WHO suggestion [122], but countries independently develop their own preparedness and response operations to mitigate the spread of COVID-19. Among the risk indicators, disease dynamic is the most important one—based on the rapid identification, diagnosis, management and reporting of infectious cases; this is followed by the health care system protection—the prevention and control of infections in healthcare settings; and the next priority is disease control—ensuring the capacity of hospital care for patients requiring hospitalization. Additionally, the alert level is often tailored to national or even local contexts and adjusted to the economic and social situation. If economic and/or social harms from the restrictions may outweigh the benefits of mitigating the spread of COVID-19, jurisdictions may decrease the level by one increment. Thus, among risk indicators connected with public health, economic and social harms should also be considered and alert levels are suggested to be established.

Table 5. Example of indicators and measures in alert system suggested for emerging infectious diseases, as COVID-19.

Risk Indicators					Alert Level	Measures	
Disease Dynamic	**Health Care System**	**Disease Control**	**Economic Situation**	**Social Situation**		**Community**	**Transportation**
extremely high burden, many outbreaks	overloaded healthcare, shortage of medical workers	very limited ability to isolate cases and quarantine contacts	un-manageable	irreversible	**High**	controlled essential services and travel outside home, only telemedicine, schools closed (e-learning), no mass gatherings, no visits to nursing homes, recreation closed	none, private transport only
high burden, many outbreaks	limited capacity of healthcare, many infections among care workers	limited ability to isolate cases and quarantine contacts	very stressed but manageable	policy support highly required	**Medium high**	only essential services, only essential travel outside home, only telemedicine, schools closed (e-learning), no mass gatherings, no visits to nursing homes, recreation closed	strong restrictions
moderate burden, few outbreaks	same capacity, same infections among care workers	same ability to isolate cases and quarantine contacts	stressed but manageable	requiring policy support	**Moderate**	only essential travel outside home, safety precautions at work, health care services (telemedicine, essential and chronic care), schools closed (e-learning), restaurants closed (pick-up only), limited mass gatherings, recreation closed	minor restrictions
low burden, rare outbreaks	full capacity, rare infections among care workers	ability to isolate cases and quarantine contacts	managing	reversible	**Low**	some safety measures at work, health care services, education, mass gatherings, recreation	full with reinforcements
rare cases	full capacity, no infections among care workers	ability to isolate all cases and quarantine contacts	managing	almost no stress	**New normal**	minimal safety measures at work, health care services, education, mass gatherings, recreation	full
no cases	standard	no control	normal	no stress	**Normal**	no safety measures	full

3. Results

Scenarios for Reducing Epidemic Risk in Public Transport

Public transport operators should focus on making travel as safe as possible when social distancing is in effect so that those without a car or disabled people are able to travel. In particular, low-income people who tend to not have a car are often unable to work from home and have to continue to use public transport. Although public transport services are strongly dependent on revenue from tickets, public operators should be encouraged to not drastically reduce the frequency or capacity of public transport (as a result of fewer passengers). Instead, they should maintain a level of service to allow passengers to keep a safe distance to one another. Because many public transport operators have seen a drop in revenue and are experiencing financial problems, governments may temporarily provide public transport operators with funding. If social distancing rules were to be continued over an extended period, operators should consider rearranging the interiors of public transport vehicles (e.g., more separate compartments). This would help passengers to avoid contact and travel safely [123]. Singapore [124] is an example, where a partial closure of bus routes and a limiting of bus capacity may delay the spread of the epidemic.

Ref. [125] concludes that demand for passenger transport will continue to be lower after COVID-19 compared to the state before the pandemic. The main causes include a stronger role of working remotely and a drop in international trips, particularly for recreation. Ref. [126] claims that COVID-19 is, paradoxically, an opportunity for the transport sector to change how transport operates and to make it more resilient, safe and sustainable.

Based on this, a set of recommendations for cities and transport enterprises was formulated based on a set of pro-active actions assigned to the strategies defined in Section 2 and related to levels of epidemiological hazards [127]. Table 5 and Appendix B show the details of the proposed new guidelines.

To ensure an effective level of preparedness if there is a new wave of the SARS-CoV-2 coronavirus epidemic or another infectious agent, and to reduce the effects of public transport on the development and spread of the epidemic, the following procedures and pro-active solutions are required:

1. The carrying out of an analysis of passenger streams by commuter lines to workplaces that cannot be closed, to schools, universities or offices that may work online, and to places of recreation. Passenger streams should be estimated based on the changes that occurred during the first wave of the coronavirus. Because the public slowly becomes accustomed to the hazard, it is likely that passenger number drops during the second wave may be lower than during the first wave.
2. The carrying out of check-ups of the fleet and introduce new passenger limits per vehicle for different epidemic scenarios.
3. Based on the estimated passenger streams and vehicle capacities, variable timetables should be prepared and implemented if the epidemic scenarios change. It is particularly important to match seat supply to passenger numbers.
4. Work should begin to prepare vehicles to move from the baseline scenario 0 to 1. This means ordering and rearranging vehicles to separate the passengers' space from the driver's cabin and minimising the need for the driver to enter into the passengers' space.
5. Work should begin to prepare public transport stops to move the from baseline scenario 0 to 1. This means setting up seats spaced at the right distance, roofing the entire public transport stop as needed (shelters are to be avoided because passengers tend to aggregate there when it is raining or snowing), and planning layouts so that passengers can wait without excessive congestion.
6. Ticketing methods need revision. Smart solutions should be prevalent: contactless cards, mobile applications, and contactless screens in ticket machines. Paper tickets validated at stations or in vehicles, and the use of cash to buy tickets from the driver, should be abandoned.

7. Consideration should be given to the fact that driver–passenger contact may have to be restricted. This means new ways must be devised to help people with disabilities. Manually operated ramps should be avoided and replaced with automatic ramps or platforms adjusted to vehicle floors.
8. The carrying out of an audit of heating and air-conditioning equipment to establish how it may contribute to the spread of infectious agents inside a vehicle. A plan should be prepared for switching off or redesigning the equipment as needed.
9. The carrying out of an audit of the fabric on seats and the material used in railings, handles and surfaces that passengers touch. Materials should be used that help with disinfection and hamper the development and survival of infectious agents.
10. The carrying out of an audit of so-called hot spots such as buttons for opening doors. Where possible, doors should open automatically without the need to press buttons.
11. Preparedness for disinfecting vehicles must be ensured if the epidemic scenario changes. A plan of action should be developed if disinfection is to be carried out away from the depot (e.g., at terminal stops).
12. Personal protection equipment and disinfectants must be kept in sufficient supply. The equipment should be part of vehicle equipment or should be issued to staff.
13. The carrying out of an audit and review of existing staff uniforms. They should be of fabric that can be washed frequently and which hampers the production of infectious agents.
14. Campaigns should be run to inform passengers of the possible threats and preventive measures. They should be designed to give passengers a sense of security and keep them alert at the same time. If ill-thought-out, warnings may cause fear, leading passengers to make undesirable transport choices.
15. Funding must be ensured to support transport companies if ticket revenue falls sharply. Public transport is key to the efficient operation of cities and must be kept operational.
16. Given all the threats of the epidemic, a continued effort should be made towards sustainable transport by promoting walking and cycling routes, extending tram networks, giving more priority to public transport vehicles and ensuring road safety.
17. Preparing staff for work under the conditions of an epidemic, with regular training to increase their knowledge and competence in this area.
18. Launching and maintaining a helpline for the employees, which enables immediate help in specific cases.

4. Conclusions

This review of research and actions in the area of restricting the risk of virus spread while using public transport showed that different countries handle this challenge differently. There is a range of actions from not very restrictive to a complete closure of public transport. Behaviour, including transport behaviour, also differed significantly from country to country during the COVID-19 epidemic. As a result, some flexibility is advised in how measures are introduced to ensure that they address the behaviour. The objective, however, should be to keep passengers and public transport staff safe by developing a basic range of actions to support the organisation and operation of public transport under different epidemic scenarios. Public transport operation must change even if COVID-19 is fully under control. The threat of a new epidemic will always be there. The work presented by the authors forms a public transport policy which is ready to address threats of varying intensity.

New research by the authors will extend public transport risk assessment by taking into account risk groups and the severity of the epidemic as measured by the number of deaths. The research will also include new models of how the epidemic develops for different scenarios, with a special focus on social distancing on public transport and in passenger waiting and exchange zones. Other important aspects in future work will include the effects of service frequency, closures of selected routes and other restrictions on the transport behaviour of the population of selected cities.

The sets of pro-active measures for selected epidemic scenarios presented in the article may offer support to local authorities and public transport operators. It is, however, important to realize that besides some similarity, each infectious disease is disseminated with its own logic. Thus, public transport and accompanying infrastructure need to become bio-resilient to already known and new occurring diseases. This is of high importance, in terms of both public health and biosecurity. In the next steps, it is important to develop and implement tools for public transport management to ensure safety and tackle epidemic hazards.

Passengers' return to public transport in cities is essential because of road congestion and increased energy use. Without the feeling of safety, particularly in the context of protection against the COVID-19 virus, this will be very difficult and will cause further economic and environmental losses including those related to energy consumption.

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Appendix A. Changing Habits of Mobile Phone Users, and Daily COVID-19 Cases per Million Habitants

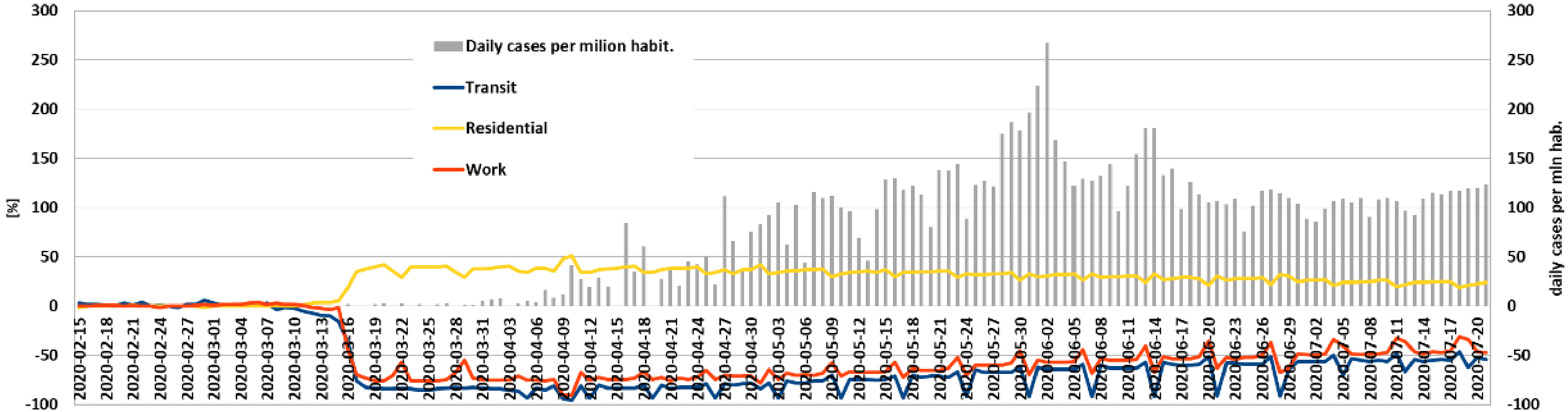

Figure A1. Changing habits of mobile phone users in Lima (Peru), and daily COVID-19 cases per million habitants.

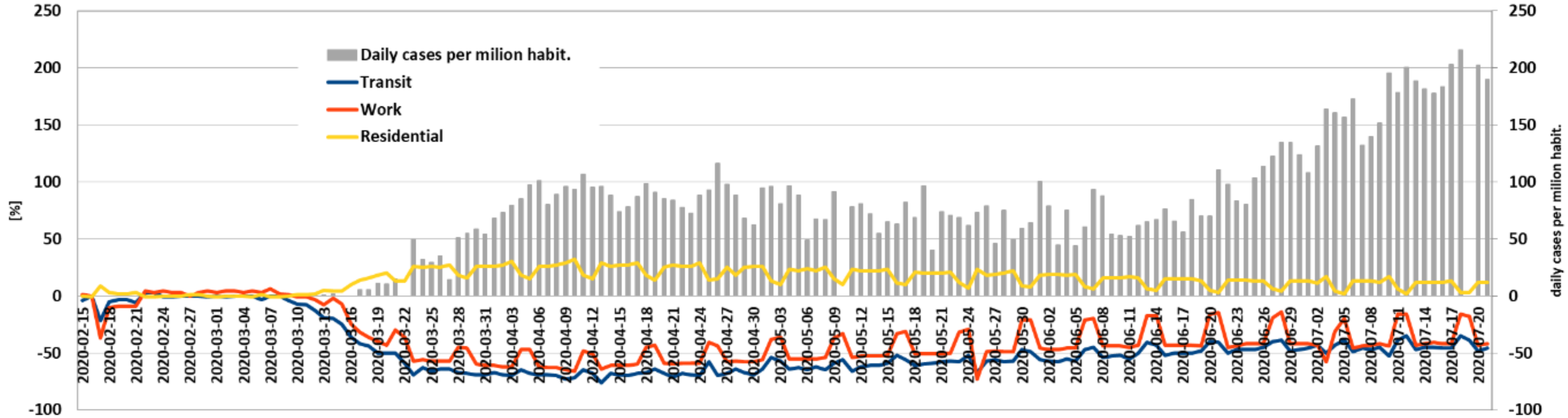

Figure A2. Changing habits of mobile phone users in New York (USA) and daily COVID-19 cases per million habitants.

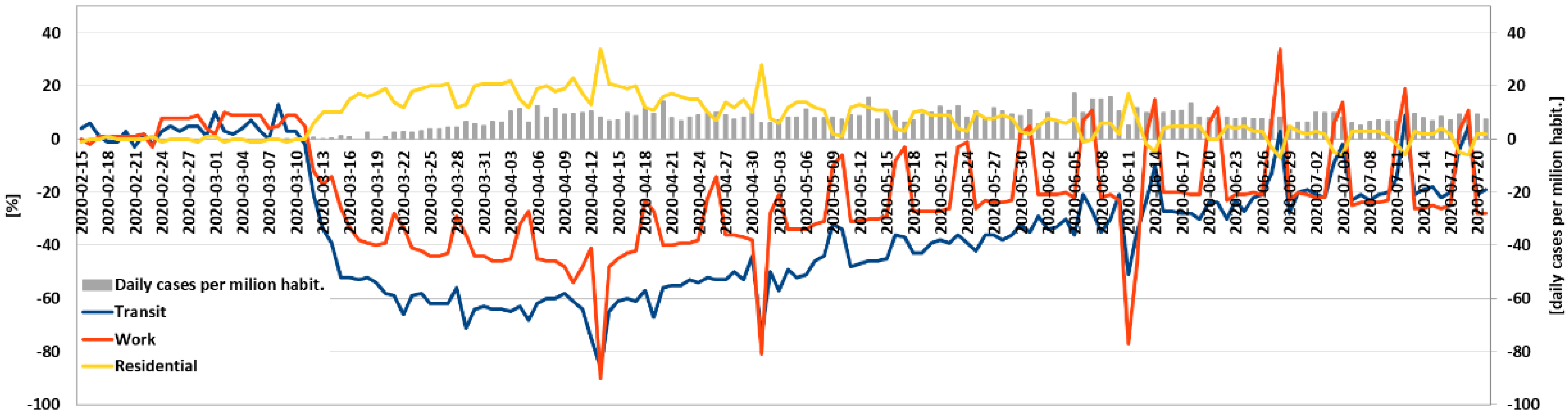

Figure A3. Changing habits of mobile phone users in Poland and daily COVID-19 cases per million habitants.

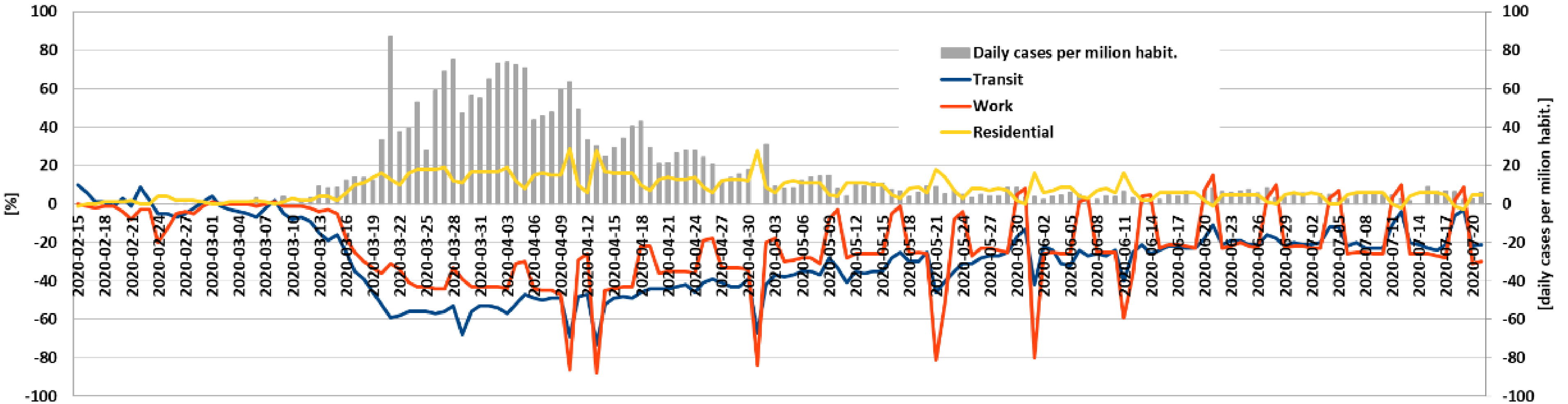

Figure A4. Changing habits of mobile phone users in Germany and daily COVID-19 cases per million habitants.

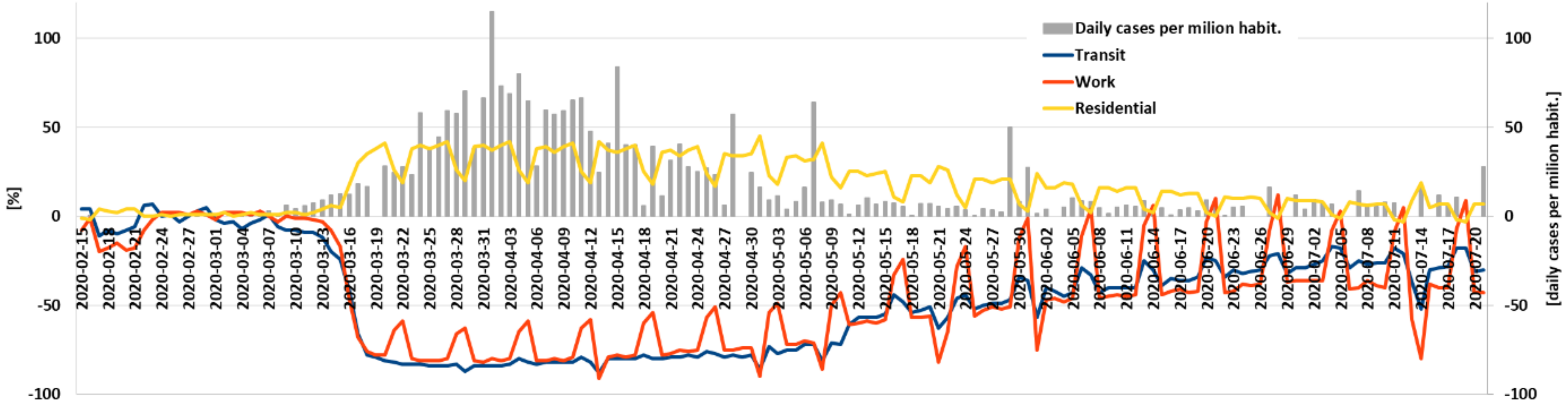

Figure A5. Changing habits of mobile phone users in Île-de-France (France) and daily COVID-19 cases per million habitants.

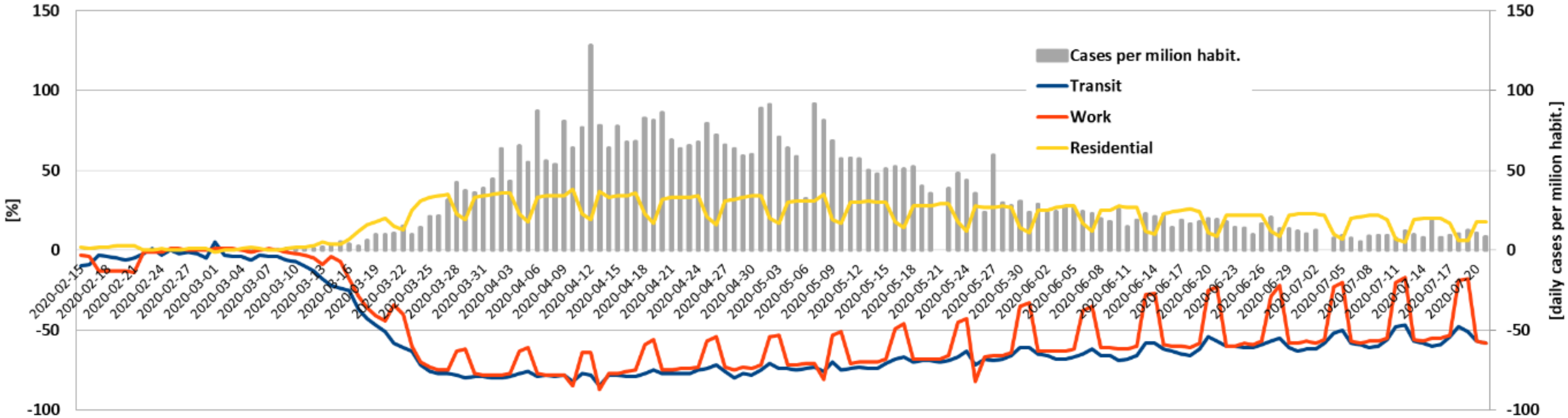

Figure A6. Changing habits of mobile phone users in London (United Kingdom) and daily COVID-19 cases per million habitants.

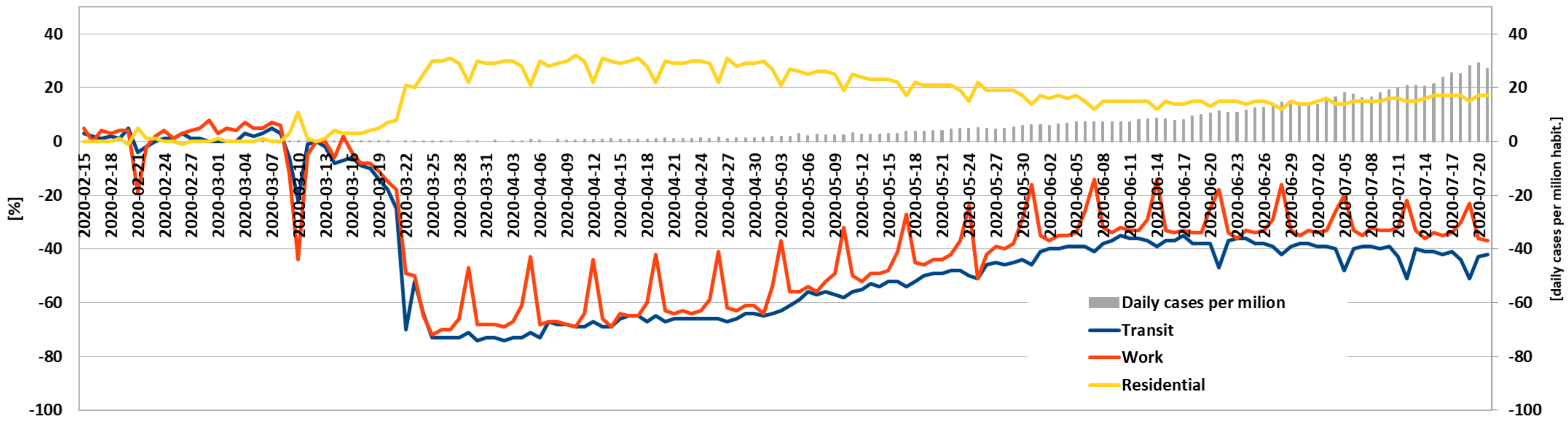

Figure A7. Changing habits of mobile phone users in India and daily COVID-19 cases per million habitants.

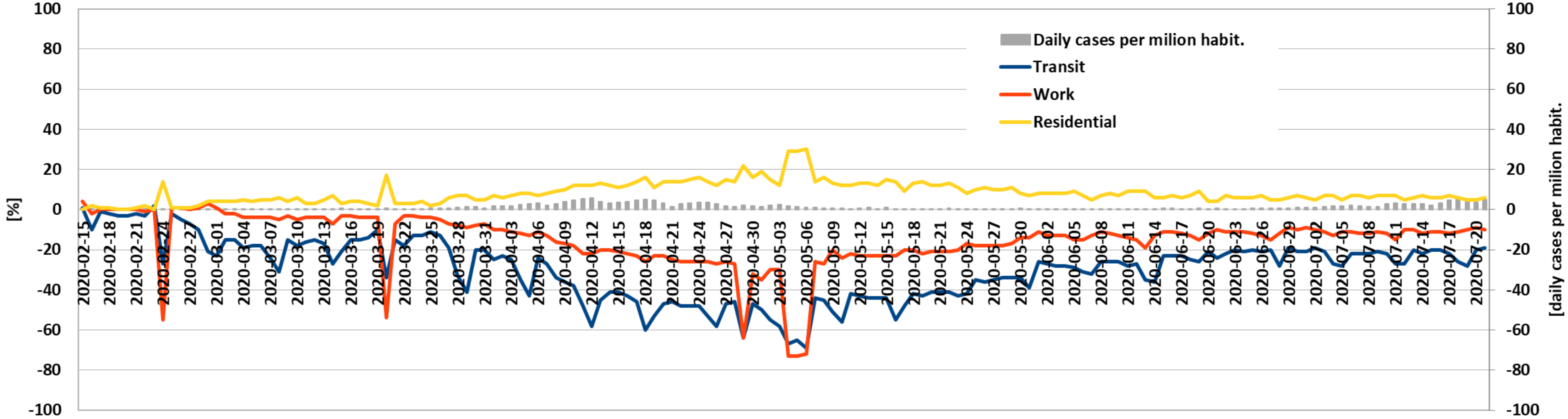

Figure A8. Changing habits of mobile phone users in Japan and daily COVID-19 cases per million habitants.

Appendix B

Table A1. Characteristics of epidemic scenarios.

Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Level of Epidemic					
	Zero	Low	Medium	High	Very high
Characteristics					
Baseline before COVID-19 epidemic	No cases, preventative measures	Stable or falling number of cases	Slight increase in cases	Numerous cases	Lockdown
Strategy of Action					
None	ST1	ST2	ST3	ST4	ST5
Transport System Operation					
Full	Full	Full with reinforcements	Some restrictions	Strong restrictions	None
Availability of Transport					
Normal transport services	Normal transport services	Full transport services with reinforcements to reduce overcrowding	Non-essential services reduced	System available to key worker groups only	No transport services
Waiting Zone					
- Distance between passengers is not limited. - Ticket machines and surfaces cleaned sporadically - Floors or seats are not marked. - Disinfectants are not available.	- Distance between passengers not less than 0.5 m (about 0.5 m^2 per person). - Preventative disinfection of ticket machines and surfaces, once a day.	- Distance between passengers not less than 1 m (about 1 m^2 per person). - Preventative disinfection of ticket machines and surfaces (at least 2 a day after peak hours). - Put up signs to stop people from gathering in a single space. - Mark seats to ensure a distance of 1 m for those waiting.	- Distance between passengers not less than 1.5 m, which is about 2.5 m^2 per person. - Preventative disinfection of ticket machines and surfaces multiple times daily. - Introduce guidance to encourage the use of mobile ticket purchases. - Put up signs to stop people from gathering in a single space and mark spaces on floor. - Mark seats to ensure a distance of 1.5 m for those waiting. - Provide hand disinfectants for passengers.	- Distance between passengers not less than 3 m, (about 7 m^2 per person). - Disable ticket machines and make other forms of payment mandatory (mobile apps, etc.). - Disinfect surfaces multiple times daily. - Put up signs to stop people from gathering in a single space and mark spaces on floor or surface. - Mark seats to ensure a distance of 3 m for those waiting. - Provide hand disinfectants for passengers. - Provide shoe disinfectants for passengers.	- Close waiting zones.

Table A1. *Cont.*

Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
			Passenger Exchange Zone		
No requirements regarding passenger exchange zone.	- Passenger exchange zone should be free from obstacles to prevent crowding.	- Mark floors or surfaces to channel passenger streams and stop the mixing of boarding and disembarking passengers.	- Mark floors or surfaces to channel passenger streams and stop the mixing of boarding and disembarking passengers, and maintain a distance of not less than 1.5 m.	- Passengers waiting to board a vehicle must wait outside the passenger exchange zone until all passengers have disembarked.	- Close passenger exchange zones.
			Vehicle		
- Vehicle capacity defined as all occupied seats and 0.125 m^2 per person standing. - Ticket machines and surfaces cleaned sporadically - No markings of floors or seats. - No disinfectants. - Air-conditioning and heating operating in a closed system, no detailed requirements regarding filters.	- Vehicle capacity defined as all occupied seats and 0.5 m^2 per person standing. - Normal operation of air-conditioning, active door buttons, ticket machines. - Surfaces touched by passengers cleaned and disinfected once a day, after the vehicle has returned to base.	- Vehicle capacity defined as all occupied seats and 1 m^2 per person standing. - Introduce vehicle floor markings to help with keeping passenger distance. - Normal operation of air-conditioning, active door buttons, ticket machines. - Equip air-conditioning with filters to reduce the spread of microorganisms. - Surfaces touched by passengers cleaned and disinfected twice a day after peak hours.	- Vehicle capacity defined as half of occupied seats (or a seat unoccupied next to an occupied one) and 2.5 m^2 per person standing. - Introduce vehicle floor and seat markings to help with keeping passenger distance. - Increase vehicle airing and limit the use of closed system air-conditioning and heating. - Air-conditioning to be equipped with filters limiting the spread of microorganisms—at least HEPA filters where possible. - Surfaces touched by passengers should be cleaned and disinfected every time the vehicle waits at the terminal stop. - Restrict the use of buttons and touch screens by passengers—open doors remotely or use automatic devices, switch off ticket machines and recommend the use of mobile applications.	- Plan seat distribution to ensure that passengers keep the right distance. Only selected seats in a vehicle can be used. - Switch off all touch-operated devices. - Switch off air-conditioning and heating operating in a closed system. - Air the vehicle at each stop and terminal stop. - Surfaces touched by passengers should be cleaned and disinfected every time the vehicle waits at the terminal stop. - Restrict the use of buttons and touch screens by passengers—open doors remotely or use automatic devices, switch off ticket machines.	- No passenger services.

Table A1. *Cont.*

Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Operator Preparedness					
- No regulations regarding staff uniform or personal protective equipment. - No analyses or supplies of disinfectants or personal protective equipment.	- Provide staff with personal protective equipment such as disposable gloves, disinfectants - Supply disinfectants, technical materials and protective equipment, prepare for the possibility of raising the scenario to ST3. - Keep staff and vehicles at appropriate level to follow the requirements of ST2.	- Equip staff with personal protective equipment and masks. - Introduce safety and disinfection rules for all jobs. - Conduct an analysis of filling in for key personnel if unable to work. - Supply disinfectants, technical materials and protective equipment, prepare for the possibility of raising the scenario to ST3.	- Equip staff with personal protective equipment and masks. - Introduce safety and disinfection rules for all jobs. Vehicles to be operated in gloves and masks to be worn upon leaving driver cabins. - Conduct an analysis of filling in for key personnel if unable to work. - Supply of disinfectants, technical materials and protective equipment to be maintained at level of ST3 for 30 days with the possibility of going up to ST4. - Check health of staff reporting for work.	- Equip staff with personal protective equipment, outfits, eye-glasses and masks. - Masks and gloves to be worn at work, work clothes to be washed by operator at shift end. - Conduct an analysis of filling in for key personnel if unable to work. - Supply of disinfectants, technical materials and protective equipment to be maintained at level of ST4 for 14 days or at level of ST3 for 30 days. - Check health of staff reporting for work. - Regular testing of staff for infectious factors.	- Key personnel which is critical for the operation of the company works to the most rigorous sanitary regime with no contact with passengers. - Conduct an analysis of strategies on filling in for key personnel if unable to work. - Continuous monitoring of company preparedness to move into ST4. - Supply of disinfectants, technical materials and protective equipment to be maintained at level of ST4 for 14 days or at level of ST3 for 30 days. - Check health of staff reporting for work. - Regular testing of staff for infectious factors.
Staff Coming into Contact with Passengers					
- Open driver cabins, not separated from passengers. - Same door for staff and passengers. - Frequent entry into passenger space. - Tickets sold and checked without any protection.	- Physically separate driver cabins using a glass panel and provide a separate exit for the driver (where possible). - Tickets to be purchased from the driver only if no other form to buy or check tickets is possible.	- Seal driver cabin (where possible). - Any ticket sales by driver must be paid using contactless forms. - Limited ticket checks, controllers wearing safety equipment (masks, gloves) and contactless terminals.	- Seal driver cabin (where possible). - Introduce a buffer zone between driver cabin and passenger space, 1.5 m wide. - Remove contact between driver and passengers, no tickets sold by driver. - Only allow staff to be in passenger space if absolutely necessary. - Tickets checked only at platforms.	- Seal driver cabin (where possible). - Introduce a buffer zone between driver cabin and passenger space, 3 m wide. - Passengers and staff not allowed to be in the same section of the vehicle (except emergencies). - Ticket checks replaced with access control for those authorized.	- No contact between staff and passengers.

Table A1. *Cont.*

Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Staff drills and preparedness (in a transport company) in case of an epidemic:					
-None	- Introduce response procedures in case of an atypical event that occurred on board a vehicle which may lead to an infection risk—evacuation, separation, disinfection, - Staff training in case they come into contact with a potentially infected person. - Staff training in case the epidemic alert level goes up.	- Staff training and reminders regarding daily vehicle disinfection routines and behaviour towards passengers, - Staff training on the possibility of increasing epidemic risk levels.	- Staff training and reminders regarding daily vehicle disinfection routines and behaviour towards passengers, - Staff training on handling stress and dealing with people when they must be refused travel (vehicle overcrowding), - Regular training on the use of personal protection equipment, - Communicate to staff the possibility that they may come into contact with an infected person, - Staff training on the possibility of increasing epidemic risk levels.	- Staff training on ways to select passengers before they board the vehicle, - Staff training on handling stress and dealing with people when they must be refused travel (vehicle overcrowding), - Regular training on the use of personal protection equipment, - Communicate to staff the possibility that they may come into contact with an infected person, - Staff training on the possibility of increasing epidemic risk levels.	- Staff training to ensure preparedness to reintroduce services when epidemic risk is lower.
Route Operation					
- Normal transport service. - Allow overcrowding of vehicles.	- Normal transport service while restricting capacity.	- Normal transport service, on particularly busy lines (especially for commutes to work or school) add services to reduce overcrowding.	- Reduce service frequency on less important routes, maintain service on key lines. - Action to reduce vehicle overcrowding, response if overcrowding occurs.	- Suspend less important lines. - Operate vehicles on key lines only to match demand. - Strict control of passenger numbers and dynamic response to needs as they arise.	- No service.
Passenger Guidelines					
- No guidelines.	- Use of hygiene products (wash hands) after trips. - Cover mouth and nose if unwell. - Encourage the use of mobile apps for travel.	- Use of hygiene products (wash and disinfect hands) after trips. - Encourage all passengers to cover mouth and nose. - Encourage passengers to not converse. - Encourage passengers to use mobile apps for travel. - Avoid travel if unwell.	- Use of hygiene products (wash and disinfect hands) during and after trips. - All passengers must cover mouth and nose. - Encourage the use of disposable gloves for travel. - Encourage passengers to travel off-peak. - Avoid travel if unwell, for the elderly and people with chronic diseases or reduced immunity. - Mobile apps to be used by all or tickets to be bought outside the vehicle.	- Use of hygiene products (wash and disinfect hands) during and after trips. - All passengers must cover mouth and nose. - Everyone must wear disposable gloves when travelling. - Travelling not allowed for people with disease symptoms.	- No passenger services.

Table A1. *Cont.*

Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Critical Analyses					
- No analyses conducted.	- Analysis of passenger streams and enhancements for the busiest lines to avoid overcrowding. - Regular vehicle cleanliness analyses.	- Analysis of changes in passenger behaviour. Introduce enhancements on key lines. - Regular analysis of vehicle cleanliness for infectious factors.	- Analysis of drop in passenger numbers and responses to decreasing demand to maintain transport company profitability as much as possible (external funding necessary). - Daily analysis of vehicle cleanliness for infectious factors.	- Analysis and design of a new transport system addressed to key workers only. - Analysis of vehicle cleanliness for infectious factors at each terminal stop.	- Analysis and assessment of fleet and infrastructure condition while disused to ensure that it can resume operation as soon as possible.

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