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PROBABILITY OF TRANSMISSION OF SARS-COV-2 VIRUS PATHOGENS IN LONG-DISTANCE PASSENGER TRANSPORT

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Abstract:

This paper presents a description of the methodology developed for estimation of pathogen transmission in transport and the results of the case study application for long-distance passenger transport. The primary objective is to report the method developed and the application for case studies in various passenger transport services. The most important findings and achievements of the presented study are the original universal methodology to estimate the probability of pathogen transmission with full mathematical disclosure and an open process formula, to make it possible to take other specific mechanisms of virus transmission when providing transport services. The results presented conducted an analysis on the mechanisms of transmission of SARS-CoV-2 virus pathogens during the transport process, to examine the chain of events as a result of which passengers may be infected. The author proposed a new method to estimate the probability of transmission of viral pathogens using the probability theory of the sum of elementary events. This is a new approach in this area, the advantage of which is a fully explicit mathematical formula that allows the method to be applied to various cases. The findings of this study can facilitate the management of epidemic risk in passenger transport operators and government administration. It should be clearly emphasised that the developed method and estimated values are the probabilities of pathogen transmission. Estimating the probability of transmission of the SARS-CoV-2 virus pathogen is not the same as the probability of viral infection, and more so the probability of contracting COVID-19. Viral infection strongly depends on viral mechanisms, exposure doses, and contact frequency. The probability of contracting COVID-19 and its complications depends on the individual characteristics of the immune system, even with confirmed viral infection. However, it is undoubtedly that the probability of transmission of the SARS-CoV-2 virus pathogen is the most reliable measure of infection risk, which can be estimated according to the objective determinants of pathogen transmission.

Keywords: *SARS-CoV-2 pandemic, pathogen transmission, passenger transport*

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1. Introduction

One of the most important and fundamental factors of transportation policy analysis, planning, and evaluation is safety of transport systems. The definition of safety in the transport system changed irreversibly in 2020, especially when considering passenger public transit and urban mobility (Burdzik et al., 2023). The epidemic of the SARS-CoV-2 virus, which very quickly turned into a global COVID-19 pandemic, has changed the behaviour of people around the world and the perception of safety, especially in public spaces (Esmailpour et al., 2022). In the case of transport, safety, previously considered in terms of human accidents (Graba et al., 2023) or cargo damage, has been perceived in the context of the risk of infection and epidemic threats since the outbreak of the COVID-19 pandemic (Murawski et al., 2022).

Transport also plays an important role in the aspect of the epidemic. Due to the functions of moving from the starting point to the destination implemented, it naturally affects the range and pace of the spread of the epidemic (Kurek et al., 2022). This aspect is particularly important in passenger transport, especially in urban agglomerations. Taking all this into account, collective public transit should be considered strategic for monitoring and limiting the spread of the epidemic (Burdzik and Speybroeck, 2023). Therefore, epidemic safety in transport should currently be one of the most important and primary criteria when defining transport policy and developing mobility strategies, especially in large urban agglomerations (Burdzik, 2023). In this case, the concept of security is transferred directly to passengers, but also to the rest of the population as a result of the impact on the pace and extent of the spread of the epidemic. Therefore, it is the social responsibility of transport policy in a new sense (Dávid et al., 2022).

The transport sector, which has always required a balance and a compromise between the financial effect and mobility, especially urban mobility, as well as a sustainable transport policy in terms of minimising the negative impact on the environment as opposed to individual transport, faced new challenges (Ulbrich, 2021). Attempts to meet the needs of the image of an epidemically safe public transit and the restrictions of state governments often boiled down to reducing the number of travelers in collective public transport, e.g. to 50% (or even 30%) of capacity. However, it is difficult to find a methodological, mathematical, or sanitary basis for determining such safety measures. For this purpose, the probability of transmission of pathogens while travelling in public transport should be taken as a very important measure that will indicate the legitimacy of transport operators' actions in the field of ensuring epidemic safety for passengers and reducing the rate of spread of the epidemic. And this problem that is the subject of the research described in this paper. The authors (Y. Chen et al., 2020) of the study on blocking and controlling the traffic are urgent in the early stage of epidemic. Another example is presented in (Sangiorgio and Parisi, 2020), in which the parameters involved in the spread of Covid-19 in urban districts are quantified. The weights are defined and calibrated using the multicriteria approach and the GRG method. The hazard has all three related parameters of intermediate importance: Infected people (13%), not immune people (13%) and Mobility (7%). It shows the influence of transport on the spread of the epidemic.

This problem is extremely important. Should we ask a question follow the (Mashrur et al., 2022) ‘Will COVID-19 be the end for the public transit?’. (Mashrur et al., 2022) research shows some evidents that passengers were sensitive to the daily number of new covid cases and vaccination rollouts. The presented shows that the COVID-19 outbreak and subsequent restriction on mobility had an unprecedented impact on travel demand. The pandemic posed unexamined changes in the travellers’ mode choice of travel mode. The results of (Mashrur et al., 2022) show that among all the travel modes, public transit was the most affected, with ridership dropping almost 80 % during the first wave of the COVID-19 pandemic in the study area.

Therefore the problem of probability of SARS-CoV-2 pathogen transmission in transport has a clear policy concern and should be of interest for practice. This study conducted an analysis on the mechanisms of transmission of SARS-CoV-2 virus pathogens during the transport process, to examine the chain of events as a result of which passengers can be infected. The author proposed a new method to estimate the probability of transmission of viral pathogens using the probability theory of the sum of elementary events. This is a new approach in this area, the advantage of which is a fully explicit mathematical formula that allows the method to be applied to various cases. The primary objective is to report method developed and application for case studies as various variants of public transit. Findings from this study can facilitate managing epidemic risk in public transport operators and government administration, e.g., by selecting appropriate variants of transit depending on the current epidemic level in a given region.

Estimating and managing risks in transport has always been an important research problem and a major scientific challenge (Szaciłło et al., 2021) (Kukulski et al., 2023) (Niewczas et al., 2023). Estimating the risk of COVID-19 infection has become the subject of research by many scientists around the world (Park et al., 2021) (Staniuk et al., 2022). Scientists use different assumptions, approaches, and methods to assess the risk of infection. Risk perception refers to the instinctive evaluation of the people regarding a hazard they might be exposed to (Cori et al., 2020). Analysing risk perception and identifying factors influencing risk perception are important to understand people's risk-taking behavior. The risk perceptions of COVID-19 transmission in different travel modes have been studied in (Zafri et al., 2022).

2. Epidemics models

During the analysis and forecasting of epidemic spread, the probability of pathogen transmission plays a crucial role. It determines, among other factors, the pace and extent of epidemic development. In the case of the SARS-CoV-2 virus, an additional aspect was the time between infection and the appearance of symptoms, which allowed the pathogen to be transmitted by asymptomatic carriers. When analyzing the progression of an epidemic and implementing control and preventive actions, it is of utmost importance to identify sources of pathogen transmission. One such source is transportation, and due to its dynamic nature, it represents a particularly challenging focal point to control. Therefore, the author decided to develop a methodology which would make it possible to isolate an additional group of infections in the transport sector, both in general and in a breakdown into specific groups of transport services.

The most widespread epidemic model is SIR (Susceptible-Infected-Recovered), which represents a system of relationships between: S – susceptible individuals, I – infected and infectious individuals, and R – recovered individuals. Unfortunately, one of the assumptions of this and other models is that the incubation period is short enough to disregard it, meaning that a susceptible individual who has become infected falls ill immediately. In the case of the SARS-CoV-2 virus, the incubation period is much longer, and many carriers are asymptomatic. This makes it necessary to apply different epidemic models. The reproduction rate R_t is one of the most important parameters used in modelling (predicting) of the spread of an epidemic. It models the average number of secondary infections at the given time and which is strongly correlated with current restrictions. A sample model representing the impact of restrictions on the spread of an epidemic has been provided in (Flaxman et al., 2020), where the effects of individual restrictions are estimated on the basis of data acquired from many countries. The authors of the paper (Flaxman et al., 2020) have discussed six interventions, one of which comprises the other five interventions, these being timing of school and university closures, self-isolating if sick, ban on public events, any government intervention in place, implementing a partial or complete lockdown, and encourage social distancing and isolation.

The effect of each intervention is assumed to be multiplicative. Therefore, $R_{t,m}$ is a function of intervention indicators $I_{k,t,m}$ in place at time t in country m :

$$R_{t,m} = R_{0,m} \cdot e^{-\sum_{k=1}^{6} \alpha_k I_{k,t,m} - \beta_m I_{5,t,m}} \tag{1}$$

where:
$R_{0,m}$ – component of the exponential form to ensure the positivity of the reproduction number (it appears outside the exponential),
$I_{k,t,m}$ –indicator variable for intervention k,
α_k – impact of the kth intervention,
β_k – random effect of the kth intervention,

The model proposed in (Bracher et al., 2021) additionally (besides the death rate data) uses data on testing and new diagnoses, thus ensuring better matching. Another important parameter is the ratio of people diagnosed daily to the daily number of all infected persons. This value has a direct effect on the estimation of the IFR (Infection Fatality Rate), which is the probability of death given the infection. The IFR is derived from the estimates presented in

(Verity et al., 2020), which assume homogeneous attack rates across age groups. The adjusted IFRa is then given by (Burdzik, 2022):

$$IFR_a = \frac{AR_{25-44}}{AR_a} \cdot IFR'_a \quad (2)$$

where:
$AR_{25\text{-}44}$ – is the predicted attack rate in the 25–44 years age group.
The articles (Verity et al., 2020) (Walker et al., 2020) present calculations performed to obtain general IFR estimates for different age groups in China and countries across Europe, adjusted for both demography and age-specific attack rates.
The model developed by (Bracher et al., 2021) takes into account the effects of four types of intervention. Additionally, it was modified to include daily data on diagnosed cases and extended with data specific to Poland. Thus developed, the SEIR model assumes that there are four groups in the population: S - group of people susceptible to infection), E - group of people exposed to infection but not infectious, I - group of people who are infectious to others in the population and R- group of people who have ceased to infect, e.g., by isolation or recovery. In addition, recoveries and fatalities across the population are estimated on the basis of the size of the R group.The basic hypothesis underlying the SEIR model is that all individuals in the model will perform the four roles as time passes. The transmission rate can be estimated from the sample averages calculated in individuals. The probability of infection of susceptible i via contact with infected j as follows (Colubri et al., 2020):

$$p_{i,j} = 1 - \exp\left(-[a_0 + a_1 X_i]\left[b_0 + b_1 Y_j\right]\right) \quad (3)$$

Another example of adaptation of the SEIR model is the application of the Bayesian network (Bracher et al., 2021).
Another approach which assumes that the Gaussian process regression methodology is applied to forecasting as well as to the COVID-19 infections, which may be used in dynamic and chaotic systems, has been presented in (Arias Velásquez and Mejía Lara, 2020a, 2020b).

3. Materials and methods

The issues of infection risk assessment in transport have been investigated in numerous studies reported since the outbreak of the COVID-19 pandemic. However, the vast majority of them are concerned about modeling the spread of the virus in the air. This does not allow for an assessment of the risk of infection. Also, the second source of infection, which is contact with an infected surface, is actually completely ignored. In addition, most of the presented studies are limited to specific means of transport (e.g. train, air plane), and the methodology used in the form of virus spread models or post factum analysis of statistics of infected passengers makes their use in other cases practically impossible. Therefore, the author adopted the following research assumptions:

– analysis of studies on the probability of infection or pathogen transmission for single events, e.g. touching an infected surface,
– identification of the chain of events in which all activities with pathogen transmission mechanisms occur (droplets, surface touch, person touch),
– estimation of the total probabilities of pathogen transmission, taking into account subsequent combinations in the chain of events in the transport process.

As a result, an identified and fully explicit chain of events is obtained, consisting of successive activities containing potential pathogen transmission mechanisms and an open mathematical formula that allows estimation of the cumulative probability. It should be clearly emphasised that the developed method and the estimated values are the probabilities of pathogen transmission and not the probability or risk of infection. Estimating the likelihood of infection requires consideration of the share of carriers of the virus (pathogen) in the population as well as the peculiarities of the population's immune system, e.g. depending on age or vaccination.

3.1. Identification of the mechanisms of potential pathogen transmission in passenger transport

SARS-CoV-2 is perceived to be transmitted primarily through person-to-person contact, through droplets produced while talking, coughing, and sneezing. Transmission may also involve other routes, including contaminated surfaces. SARS-CoV-2 is primarily transmitted through person-to-person contact, with respiratory droplets produced during talking, coughing, and sneezing acting as the main medium.

While contaminated surfaces, or fomites, may contribute to transmission, the general consensus acknowledges direct contact and respiratory droplets as the primary transmission routes. The role of fomites has been questioned (Katona et al., 2022), and initial data supporting fomite transmission was contested in a July 2020 study (Aboubakr et al., 2020). The Center for Disease Control and Prevention (CDC) affirms the possibility of infection through contact with contaminated surfaces, but deems the risk to be low (CDC, 2020). Increasing evidence points towards the respiratory route as the predominant mode of transmission for SARS-CoV-2 (Rodriguez-Nava et al., 2023). Quantitative microbial risk assessments indicate a less than one in 10,000 chance of contracting SARS-CoV-2 through fomites or secondary transmission (Science brief, 2021). Nonetheless, a comprehensive analysis of potential transmission mechanisms must incorporate the risk from fomites, even if it is minimal.

Airborne transmission is different from droplet transmission as it refers to the presence of microbes within droplet nuclei, which are generally considered particles < 5 μm in diameter, and are the result from the evaporation of larger droplets or exist within dust particles. They may remain in the air for long periods of time and can be transmitted to others over distances greater than 1 m (Benmalek et al., 2023) (Corzo et al., 2022). The study performed by (Ramajo et al., 2022) shows influence of the air flows inside the coach line bus for the virus transmission. Air flow simulation for the fully windows opening case have been depiced in Figure 1.

Additionally, the probability of viral infection depends on factors such as exposure time, distance, ventilation, number of surfaces potentially contaminated by the pathogen, and frequency of human contact with these surfaces or skin-to-skin contact. Furthermore, the probability of pathogen transmission is affected by the personal protective equipment in use, including face masks and gloves, as well as regular cleaning and disinfection of both touch surfaces and hands. Wearing a mask is found to be much more useful than washing hands for controlling the influenza A virus in the tested office setting. Regular cleaning of high-touch surfaces, which can reduce infection risk by 2.14%, is recommended and is much more efficient than hand washing (Zhang and Li, 2018).

To reduce the risk of virus infection, the principle of social distancing is commonly applied. The virus can spread by sneezing over a distance of up to 3.5 m, and on coughing – up to 6.5 m, as indicated by a computational fluid dynamics model developed to study the behaviour of droplets containing the virus (Shafaghi et al., 2020)(Xie et al., 2007). Therefore the probability of infection determined on the basis of ratio of the infected should be considered due to the area congestion. The total area consists of three zones: crowded zone, mild zone, and uncrowded zone, with different infection probabilities characterized by the number of people gathered there (Karako et al., 2020). The virus transmission mechanisms for different levels of congestion in public spaces (including in means of transport) along with an illustration of the levels of infection probability ($p_{i,j}$) and the consequences in terms of the growth of the infected population are provided in the figure 2.

It is possible to increase the distance between passengers in transport by limiting the number of passengers who can travel with the given vehicle at the same time. In addition to the distance between passengers, another important factor that affects the probability of pathogen transmission is contact with an infected person or the duration of exposure to pathogens (including airborne and surface transmission). However, the conclusion arising from the analysis of droplet transmission is that the longer one remains in the vicinity of an infected person (including an asymptomatic individual), the higher the probability of infection. According to surveys of travelling by public transport, this probability increases on average by 0.15% with every consecutive hour of travel (Hu et al., 2020). Also ventilation has been widely recognised as an efficient engineering control measure for airborne transmission (Melikov et al., 2020). A growing number of epidemiological cases provide for the possibility of airborne transmission (not only by droplets) of coronavirus diseases. (Dai and Zhao, 2020) have obtained the quantum generation rate produced by a COVID-19 infector with a reproductive number based fitting approach, and then estimated the association between infection probability and ventilation rate using the Wells-Riley equation. The infection probability established by the Wells-Riley equation is as follows (Riley et al., 1978):

$$p = \frac{C}{S} = 1 - e^{-Iqpt/Q} \quad (4)$$

where:
C – number of cases to develop infection,
S – number of susceptibles,
I – number of source patients,
p – pulmonary ventilation rate of each susceptible per hour (m^3/h),
q – quantum generation rate produced by one infector (quantum/h),
t – exposure time (h),
Q – room ventilation rate (m^3/h).

If both infectors and the susceptibles wear masks, the ventilation rate is increased 4 times equivalently. Assuming respiratory-droplet transmission, relevant infection control recommendations include maintaining social/physical distance, wearing masks, case isolation, and contact tracing (Pitol and Julian, 2020).

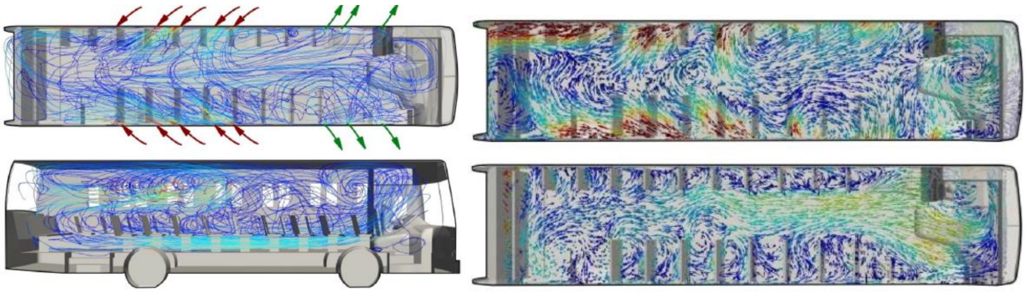

Fig. 1. Air flow simulation for the fully windows opening case (Ramajo et al., 2022)

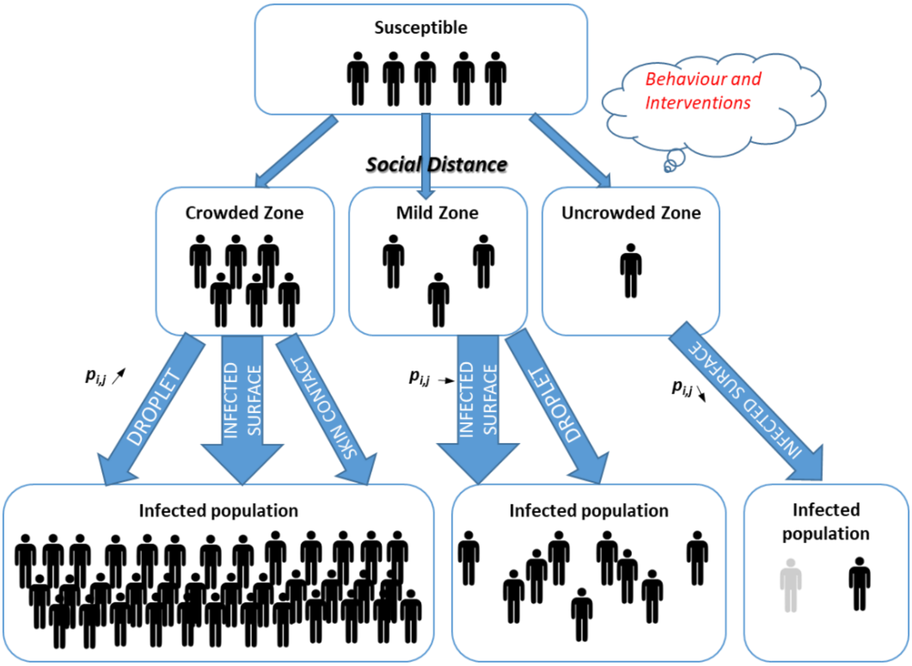

Fig. 2. Illustration of the mechanisms and probability of infection in public spaces, including in means of transport

As presented in (Dai and Zhao, 2020), if people wear masks, natural ventilation or normal mechanical ventilation can provide enough ventilation rate to ensure the infection probability of less than 1%. According to epidemic prevention, people are obliged to wear face masks or cover their mouths and noses in public spaces, and these include means of collective transport. Given the data on the virus of influenza, one can conclude how important mask use is in terms of the spread of viruses. The likelihood of being infected with influenza is 8.75%, but with the obligatory masks, this probability drops to 3.82% (Zhang and Li, 2018). Consequently, the probability of influenza infection decreases about 2.55 times assuming that people wear masks. The total risk of influenza transmission can even be reduced from 8.75% to 0.45% if the N95-type mask is worn tightly sealed by the infected person (Dai and Zhao, 2020).
Risk of the SARS-CoV-2 transmission via fomites is estimated to be low, the risk of infection of a person increases when accounting for the hundreds of objects with which people are in contact every hour, and also the thousands of frequently contacted objects (buttons in public transport). Each interaction provides an opportunity for the transmission of SARS-CoV-2. The risk of infection from multiple contact with fomites is substantially higher. Viruses can reach the mucous membrane if a person touches the mouth, nasopharynx, and eyes with a contaminated hand. Studies have shown that the mean rate of all finger contact with the lips, nostrils and eyes ranges from 0.7 h^{-1} to 15 h^{-1}. In the study by (Zhang and Li, 2018), it was estimated that the virus transfer rate from the fingertip to the mucous membranes is 35% and the amount of virus ($TCID_{50}$ - Median Tissue Culture) on all analysed surfaces ceases to increase rapidly after 3 h.
The SARS-CoV-2 virus spreads by hand-mouth pathways or by skin-borne and eye infections, which transfer from hands to skin or eyes from sources including the natural flora of the skin, and nasal passages.

3.2. Methodology for estimating the total probability of pathogen transmission in transport process

For estimating the total probability of pathogen transmission as the quantitative values, one should primarily analyse all possible mechanisms of virus transmission from one person to another, as presented in subsection 3.1. These probabilities are often calculated on the basis of models of pathogen spread in a confined space of the means of transport, represented by advanced mathematical functions. The aforementioned conditions make it difficult to adapt the said models to other means of transport, or even virtually impossible to translate them into other types of transport services, excluding transport of goods. This is precisely why the author of this paper decided to develop a universal methodology for estimating the probability of viral infection by referring to the SARS-CoV-2 pandemic, assuming full mathematical disclosure and an open process formula, aimed at making it possible to take into account specific other mechanisms of virus transmission when providing transport services.
There are no fundamental rules about infection, and even short contacts with contagious people can generate the infection. An Italian study on the outbreak of COVID-19 (Lavezzo et al., 2020) shows that the number of asymptomatic cases was roughly 45% of the entire number of cases. This means that even if symptomatic passengers are removed from travel, the probability of having contagious passengers should still be considered if the virus is active in the population and pre-symptomatic passengers are contagious. In the study presented by (X. He et al., 2020), the incubation period was estimated at 5.2 days on average and the onset of infectiousness - 2 days before the occurrence of symptoms. A higher probability of infection is estimated at ca. 12 hours before the onset of symptoms. Another important factor is the time for which the virus can survive on different formites (contact surfaces in means of transport or loads). Therefore, the contagiousness of surfaces touched by multiple passengers is a matter of concern. It should be mentioned that the overall contribution of contact transmission to the total transmission is currently deemed low.
For purposes of the methodology proposed for the determination of the probability of viral infection in transport services against the context of passenger or customer exposure in freight transport, the potential mechanisms of infection were identified for activities performed consecutively while providing the given service. Three possible virus transmission mechanisms have been taken into account:

– Droplet transmission;
– Surface/fomite contact;

– Skin contact - direct skin to skin contact with another person.

For each transport service, adequate assumptions were adopted with regard to travelling time, distance, contact surfaces, and applicable regulations (Burdzik and Speybroeck, 2023). Next, based on an analysis of the chain of events resulting from the process mapping, all activities, including the potential virus transmission mechanisms, were identified. The outcome of this procedure was a set of independent events to which, with reference to the literature review, it is possible to assign the values of probability of elementary events. The final stage was to estimate the total probability of pathogen transmission for the given transport service (Fig. 3).

The assumption underlying the method developed by the author is that it can be adapted to specific conditions of individual transport services, making it possible to establish the probability values for these services instead of averaging them for the entire transport sector or breaking it down into passenger and freight transport. This allows a comparative analysis of individual types of transport services and for considering other events taking place during the performance of the transport process, which may be sources of virus transmission. Therefore, different potential situations for individual transport services, such as paying or buying a ticket, taking a seat or a standing place, holding luggage, touching the cargo or surfaces in means of transport (e.g., seats, railings, handles). Also, the potential distances between those participating in the transport process were analysed and distinguished, taking into account the specifics of the given service, as they affect the mechanisms of virus transmission, either via droplets or by direct contact (touch). Another parameter taken into consideration when establishing the probability of elementary events occurring in transport services, assuming average values of time for specific activities conducted in respective processes, representative of the given transport service, is exposure time. All of the foregoing makes the probability values determined by that means strongly oriented towards the specificity of individual transport services, corresponding to real random events which may lead to viral infection in transport.

To calculate the total probability of infection in the given transport service, the author used the definition of the probability of a sum of independent events.

A sum of events is understood as a random event that takes place when at least one of its constituent events takes place. The sum n of consecutive events A_i, where $i = 1,\ldots,n$, can be expressed as follows: $\bigcup_{i=1}^{n} A_i$ or $A_1 \cup A_2 \cup A_3 \cup \ldots \cup A_n$.

The probability of the sum of events is expressed by what is referred to as the inclusion-exclusion formula, which assumes the following form:

$$P\left(\bigcup_{i=1}^{n} A_i\right) = P(A_1 \cup A_2 \cup A_3 \cup \ldots \cup A_n) = P(A_1) + P(A_2) + \ldots + P(A_n) - P(A_1 \cap A_2) - \ldots + P(A_1 \cap A_2 \cap A_3) + \ldots - P(A_1 \cap A_2 \cap A_3 \cap A_4) - \ldots \tag{5}$$

Independent events are such events A_i for which their intersection, i.e. the product of $A_1 \cap A_2 \cap \ldots \cap A_n$, is a null set. When this is the case, the probability of the sum of such events can be calculated using the following formula:

$$P\left(\bigcup_{i=1}^{n} A_i\right) = 1 - P\left(\bigcap_{i=1}^{n} A'_i\right) \tag{6}$$

The opposite A_i' events are also independent. The probability of the product of independent events is expressed by the following formula:

$$P\left(\bigcap_{i=1}^{n} A'_i\right) = \prod_{i=1}^{n} P(A_i') = P(A_1') * P(A_2') * \ldots * P(A_n') \tag{7}$$

Therefore, by combining these equations, one obtains the following formula to calculate the probability of the sum of n independent events:

$$P\left(\bigcup_{i=1}^{n} A_i\right) = 1 - \prod_{i=1}^{n}(1 - P(A_i)) \tag{8}$$

The above formula can be transformed into the following form:

$$P\left(\bigcup_{i=1}^{n} A_i\right) = 1 - (1-P(A_1))(1-P(A_2))\ldots(1-P(A_n)) \tag{9}$$

The probability of pathogen transmission during the execution of transportation services also depends on the likelihood of the pathogen's presence in the community, expressed as the number (percentage) of infected individuals in the population. This number should take into account both confirmed (diagnosed) cases and unconfirmed (undiagnosed) cases, including those that may be concealed, as well as individuals moving in public spaces. These values

can range from 5 to even 20 times higher (Gogolewski et al., 2022).
It should be noted that if the methodology developed by the author is to be applied to other epidemics, the current legal status and social behaviour patterns must be updated. Since the regulations in force require people to cover their mouths and noses in public spaces, it has been assumed that all those participating in the transport services described below wear masks on their faces. However, the analysis of the transport services in question includes the probability of infection for the cases of the masks are worn or not. Using data on the functioning of face masks against influenza virus, the probability of droplet infection was reduced 2.55 times (Zhang and Li, 2018).
Indirect transmission through fomites (contaminated surfaces) contributes to the spread of common respiratory pathogens (Boone and Gerba, 2007), and the evidence to date suggests that fomite transmission is possible for SARS-CoV-2. Surface-to-hand transfer and the hand-to-mucous membrane transfer were assumed proportional to the virus concentration on the contaminated surface and its transfer efficiency at both interfaces. To estimate the probability of virus transmission by touch, the author assumed the values reported in the studies by (Pitol and Julian, 2020) to determine distributions of the probability of infection by touching contaminated surfaces depending on the frequency as well as the prevalence in the given population.
Following an analysis of the data from the literature and the results of the research completed to date (Pitol and Julian, 2020) for the elementary events in which a random event of virus transmission by touching a contaminated surface may occur, a table was compiled with the values of the probability of infection dependent on the share of infected individuals in the population (prevalence rate). Moreover, analogously to the instance of wearing masks in the analysis of droplet virus transmission, the probability values were provided for hand disinfection (assuming the metric of 50% of the population) or surface disinfection by the transport operator (twice a day).

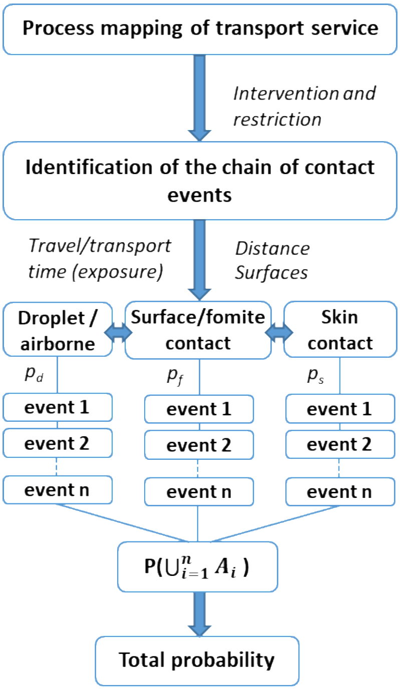

Fig. 3. Algorithm of the methodology for determining the total probability of viral pathogen transmission in transport processes

Table 1. Average median probability of infection from fomite contact for different prevalence rates and disinfection scenarios [based on (Pitol and Julian, 2020)]

Frequency of contact with surface	No hand or surface disinfection	Hand disinfection	Surface disinfection
0.2% prevalence rate			
High contact frequency [at least 3 times per hour]	10^{-8}	10^{-10}	10^{-14}
Low contact frequency [not more than once per 1–4 hours]	10^{-8}	10^{-11}	10^{-23}
1.0% prevalence rate			
High contact frequency [at least 3 times per hour]	10^{-6}	10^{-9}	10^{-7}
Low contact frequency [not more than once per 1–4 hours]	10^{-7}	10^{-9}	10^{-10}
5.0% prevalence rate			
High contact frequency [at least 3 times per hour]	10^{-4}	10^{-7}	10^{-4}
Low contact frequency [not more than once per 1–4 hours]	10^{-5}	10^{-7}	10^{-8}

The infection probability of 10^{-6} is equivalent to one person infected as a consequence of hand-to-mouth contact per million persons touching the surface. Therefore, in most analyses of the transport-related infection risk, the probability of virus transmission by touching the surface is completely ignored. But the author of this paper had decided to include it in the methodology proposed for various reasons, including the risk estimation in relation to daily hazard rates across the country, where the number of people exposed to infection was considerably higher. The analysis of transport processes made it possible to establish the frequency of contact with different surfaces depending on the type of transport service.

In order to estimate the probability of viral infection via droplets, the social distance and time of exposure to the pathogen are considered very important parameters. For transport services, this should refer to the distance between passengers or customers in the freight transport and the time of travel or contact between the participants in the freight transport process. Based on the current studies, tables of the infection probability were prepared and specific functions of droplet infection probability were assumed, conditional on the exposure time for selected means of transport, considering 100% and 50% occupancy of the available seats.

Moreover, on the relevant process maps and the identified chains of elementary (contact) events, individual activities involving a possibility of a random event with a potential mechanism of droplet virus transmission as well as their average duration times were determined. Next, in the above tables and graphs, the values of infection probability were taken each time for the pre-assumed travel time or contact activity in freight transport for the given means of transport, and then they were assigned the corresponding values of probability of elementary events.

The final measure of the probability of pathogen transmission was the probability of a sum of all independent elementary events identified in the process.

Complete description of the methodology for estimating the total probability of pathogen transmission in transport process have been presented in (Burdzik, 2022).

Table 2. Probability of infection in means of transport for different exposure times and passenger occupancy rates [based on (Sun and Zhai, 2020)]

Means of transport \ Exposure time	5 [min]	10 [min]	15 [min]	20 [min]	25 [min]	30 [min]	500 [min]	1,000 [min]
Train (100% occu.)	0.0117	0.0233	0.0350	0.0467	0.0583	0.0700	0.7000	0.9000
Train (50% occu.)	0.0083	0.0167	0.0250	0.0333	0.0417	0.0500	0.6200	0.8200
Public bus (100% occu.)	0.0300	0.0600	0.0900	0.1200	0.1500	0.1800	0.9800	1.0000
Public bus (50% occu.)	0.0225	0.0450	0.0675	0.0900	0.1125	0.1350	0.9500	1.0000
Underground railway (100% occu.)	0.0200	0.0400	0.0600	0.0800	0.1000	0.1200	0.8500	0.9800
Underground railway (50% occu.)	0.0125	0.0250	0.0375	0.0500	0.0625	0.0750	0.7400	0.9500

4. Results of estimation of probability of SARS-CoV-2 virus pathogen transmission in long distance passenger transport

To present the developed method for estimating the overall probability of pathogen transmission in transportation, case studies were conducted for representative passenger and freight transportation services. This paper presents just selected scenarios for services in long distance passenger transport, as coach line buses and long-distance train.

During the analysis of the case studies, various service implementation scenarios were considered to verify whether the developed method enables differentiation of the probability of pathogen transmission depending on the scope of operations and the organization of the transportation process. Only selected examples are presented in the article.

4.1. Pathogen transmission probabilities for the long-distance train

In accordance with the developed methodology for estimating the probability of transmission of pathogens in transport, the first stage should specify general assumptions related to the organisation of transport services, taking into account specific restrictions during the epidemic. It was assumed that long-distance train passengers, as well as employees - cashiers and conductors, and other participants of this transport service wear protective masks on their faces. The train driver is in a separate zone and has no contact with passengers. The train may be occupied with 50% of the seats or 30% of all passenger space with 50% of the seats left unoccupied. As the average travel time, it was assumed that the train travel time is 180 minutes, which is related to the time of exposure to epidemic threats.

Next step is to prepare representative flowchart as process mapping. In addition, process mapping makes it possible to analyze various scenarios for the implementation of a transport service, which can eliminate or add activities in which single mechanisms of pathogen transmission may also occur. Thanks to the use of the process description as a flowchart, the mutual relations of subsequent activities are visible, which allows for the identification of dependent and independent events, which is important in the calculation of total probability.

Based on the flowchart next step of developed methodology can be conducted. Detailed analysis of the chain of the contact events enables identification of the mechanisms of potential pathogen transmission in process of transport. In the case of a passenger service on a long-distance train during next activities the following pathogen transmission mechanisms may occur:

– ticket purchase: the passenger purchases a ticket at the ticket office at the station or at a ticket machine. In both cases, it is possible to transfer the pathogen by touching surfaces such as: money, the ticket itself, and the screen of the ticket machine. It can be assumed that the droplet transmision is not possible, because in the case of a ticket office - the cashier is separated from the customers by a glass window, while in the case of purchases at a ticket machine, there is no need to contact the other person. It is also possible to purchase a ticket in the online application or via the website, which eliminates the risk of transmission, because it does not require contact with another person or elements of infrastructure;
– boarding: as the doors are currently automatically opens at subsequent stations, there is no need for the passenger to press the door release button. Contact with other boarding passengers is possible, but it is short-timed. It is possible to touch elements such as handles or handrails. Since the driving time between stops is at least 30 minutes, we assume that these surfaces are rarely touched;
– travelling: the passenger takes the seat and the probability of touching other surfaces (handles) is minimal. On the other hand, the mechanism of droplet transmission of pathogens is significant due to the long exposure time (average 180 minutes) and closed space. The use of ventilation and HEPA filters reduces the risk of infection, however, the mechanism of transmission of the pathogen by droplets occurs. During travelling there is the additional activity as ticket validation (control). Tickets are checked contactless - using devices, so there is no possibility of infection by touch. It is possible to transmit the pathogen by droplets, but the contact time with the conductor is short - we assume 1 minute;

– deboarding: the door opens automatically, so there is no need for the passenger to press the door release button. There is a possibility of droplet transmision, but contact time with other passengers is short. It is possible to touch elements such as handles or handrails that facilitate deboarding. These surfaces are touched infrequently.

In result activities and operations are visible in which one of the mechanisms of pathogen transmission may occur (droplet, contact with a contaminated surface - fomite, skin contact). Flowchart of passenger travelling by long-distance trains with potential mechanism of virus transmission have been depicted in Fig. 4. The flowchart additionally indicates which potential transmission mechanisms of pathogens exist and which may optionally occur. The process map includes pre-travel activities such as ticket purchase and boarding, the journey (travel) itself, and deboarding activities. The analysis does not take into account the risks associated with waiting for a means of transport, although in the case of some specific transport services (air transport, underground/subway) the author conducted extended analyzes and also took into account the time and place of waiting, as well as transfer and collecting baggage.

When all the elementary activities (events) and the related mechanisms of pathogen transmission have been revealed, the values of the probability of pathogen transmission should be assigned to them based on current epidemiological knowledge and current research and reports (Table 3).

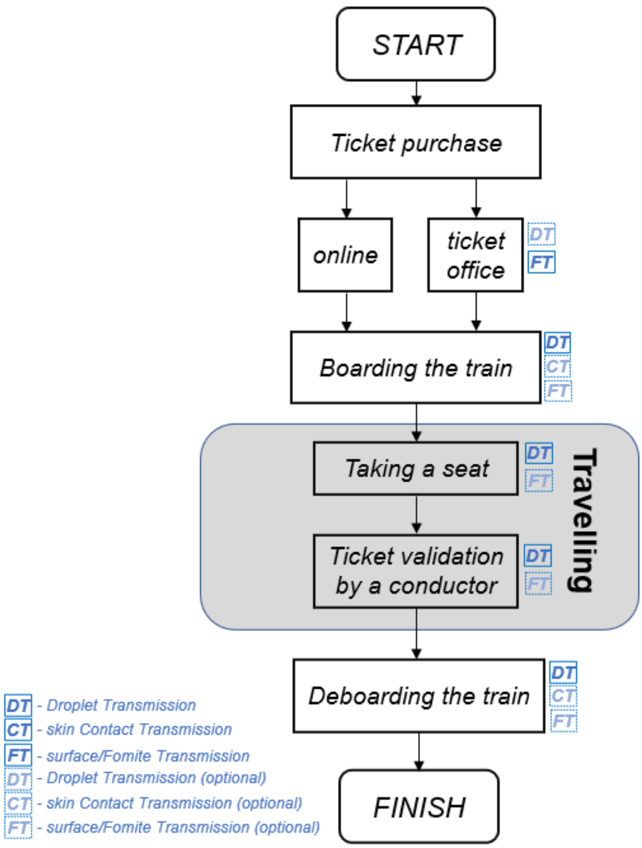

Fig. 4. Flowchart of passenger travelling by long distance trains with potential mechanism of virus transmission

Table 3. Probabilities of elementary events occurring in long-distance train

Event	Transmission mechanism	Event index	Probability of elementary event $P(A_i)$
Ticket purchase	Contact	A_1	0.0001
	Droplet eliminated	--	-----
Boarding	Contact	A_2	0.00001
	Droplet	A_3	0.0039216
Ticket validation	Contact eliminated	--	-----
	Droplet	A_4	0.0039216
Travelling	Contact eliminated	--	-----
	Droplet	A_5	0.1098039
Deboarding	Contact	A_6	0.00001
	Droplet	A_7	0.0039216

There are many scientific studies that have published the results of SARS-CoV-2 virus transmission tests for its subsequent variants on an ongoing basis over the last 3 years. These works most often concern single transmission mechanisms, such as droplets or surface-to-surface or surface-to-human transmission. Often, these studies are conducted in laboratory conditions, in which pathogen transfer mechanisms are separated, or a large group of studies consists in simulations of virus spreading via droplets in selected closed spaces. All this makes it possible to update the results by updating individual pathogen transmission probabilities according to the latest research. Thanks to the developed method, it is possible to identify these independent events and, using an explicit mathematical formula (Equation 9), it is possible to update the final results based on the latest data. This article uses the database on the likelihood of transmission by droplet and fomite contact, presented in (Burdzik, 2022) and in the section 3.2 (Table 1 and Table 2) (Pitol and Julian, 2020) (Sun and Zhai, 2020).

When, based on the map of the transport process, a complete chain of independent events has been identified, in which there are pathogen transmission mechanisms, for which single probabilities of pathogen transmission have been assigned, it is possible to estimate the total probability of pathogen transmission during the implementation of a specific transport service scenario. Using the formula (Equation 9) the total probability of transmission of pathogens is calculated, as follow:

$P = 1 – (1\text{-}0.0001)\cdot(1\text{-}0.003932)\cdot(1\text{-}0.0039216)\cdot(1\text{-}0.1098039)\cdot(1\text{-}0.003932) = 0.12034$;

$P = 12.034\ \%$

Therefore, the total probability of pathogen transmission when traveling by long-distance train is around 12%. The calculations take into account that all passengers wear protective masks and the number of travelers is limited (50%). It should be emphasized that this is the probability of transmission of pathogens and not the risk of infection. The risk of infection strongly depends on the individual characteristics of people, the percentage of infected people in the society (pathogen carriers) and the level of vaccination of the society. So, for example, in the initial stage of the epidemic (the second wave of the epidemic), when vaccinations had not yet been used and the number of active COVID-19 cases was about 1% of the population in Poland, the real risk of infection in long-distance trains was about 0.12%, which should be considered an average risk.

4.2. Pathogen transmission probabilities for the coach line bus

It was assumed that coach line bus passengers and driver wear protective masks on their faces. The bus may be occupied with 50% of the seats. As the average travel time, it was assumed that the coach line bus travel time is 250 minutes, which is related to the time of exposure to epidemic threats.

Based on the flowchart (Fig. 5) detailed analysis of the chain of the contact events enables identification of the mechanisms of potential pathogen transmission. In the case of a passenger service on a coach line bus during next activities the following pathogen transmission mechanisms may occur:

– ticket purchase: the passenger purchases a ticket at the ticket office or personally by the bus driver. In both cases, it is possible to transfer the pathogen by touching surfaces such as: money, the ticket itself. It can be assumed that the droplet transmision is limited in the case of ticekt office but when buying personally by bus driver droplet transmission can occurred, but the contact time with the driver is short - we assume 1 minute. It is also possible to purchase a ticket in the online application or via the website, which eliminates the risk of transmission, because it does not require contact with another person or elements of infrastructure;

- boarding: as the doors are currently automatically opens there is no need for the passenger to press the door release button. Contact with other boarding passengers is possible, but it is short-timed. It is possible to touch elements such as handles or handrails. Since the driving time between stops is at least 60 minutes, we assume that these surfaces are rarely touched;
- travelling: the passenger takes the seat and the probability of touching other surfaces (handles) is minimal. On the other hand, the mechanism of droplet transmission of pathogens is significant due to the long exposure time (average 250 minutes) and closed space. The ticket validation (control) during travelling can be eliminated;
- deboarding: the door opens automatically, so there is no need for the passenger to press the door release button. There is a possibility of droplet transmision, but contact time with other passengers is short. It is possible to touch elements such as handles or handrails that facilitate deboarding. These surfaces are touched infrequently.

Flowchart of passenger travelling by coach line bus with potential mechanism of virus transmission have been depicted in Fig. 5. The flowchart additionally indicates which potential transmission mechanisms of pathogens exist and which may optionally occur.

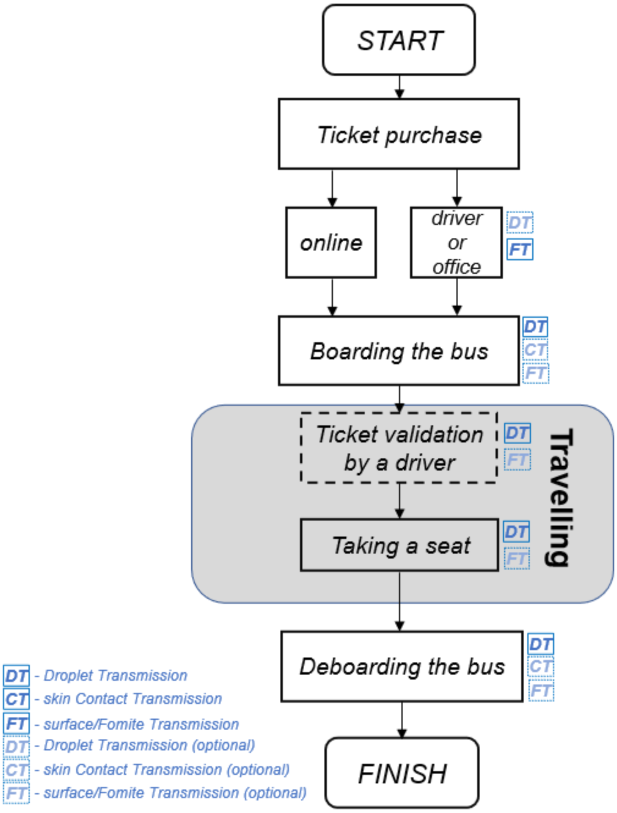

Fig. 5. Flowchart of passenger travelling by coach line busses with potential mechanism of virus transmission

Table 4. Probabilities of elementary events occurring in coach line bus

Event	Transmission mechanism	Event index	Probability of elementary event P(A_i)
Ticket purchase	Contact	A_1	0.0001
	Droplet	A_2	0.0039216
Boarding	Contact	A_3	0.00001
	Droplet	A_4	0.0039216
Ticket validation	Contact eliminated	--	-----
	Droplet eliminated	--	-----
Travelling	Contact eliminated	--	-----
	Droplet	A_5	0.1568627
Deboarding	Contact	A_6	0.00001
	Droplet	A_7	0.0039216

Thus, the total probability of pathogen transmission when traveling by coach line bus is around 16.7 %. The calculations take into account that all passengers wear protective masks and the number of travelers is limited (50%). Again it is the probability of transmission of pathogens and not the risk of infection. For the the second wave of the epidemic, when the number of active COVID-19 cases was about 1% of the population in Poland, the real risk of infection in coach line busses was about 0.17%, which should be considered a significant risk.

5. Conclusions

The problem of estimating the probability of viral infection in transport is a huge challenge. This is due to the nature of transport processes, in which there are many activities, in various combinations, during which there is a possibility of transmission of virus pathogens. In addition, the dynamic nature, lack of allocation and continuous flows (exchanges) of passengers and goods cause difficulties in monitoring epidemic threats. The probability of pathogen transmission is not equivalent to the probability of viral infection. To determine the overall probability of viral infection attributable to the provision of transport services, the probability resulting from the number of active infections in the population must be taken into account. Other infection risk factors, such as individual immunity, vaccinations, additional prevention (gloves, disinfection, social distancing), should be considered additionally. Therefore, the identification of elementary events and the calculation of the sum of transmission probabilities for these events seem to be more readable. Thanks to this, the total probability of pathogen transmission is estimated, which can then be converted into the probability of infection using the current and latest pathogen transmission rates and the statistical number of pathogen carriers in the community.Furthermore, according to the estimates mentioned above, these values should be adjusted by considering undiagnosed active cases.

The article describes the author's method of estimating the probability of pathogen transmission in transport, described in detail in (Burdzik, 2022). In addition, the results of the application of this method are presented and the probability values for passenger transport in long-distance trains and line coaches are compared. The calculated values assume epidemic conditions, i.e. wearing protective masks and limiting the number of passengers in vehicles. The main source of the difference (4.65%) in the probability of transmission of pathogens is the exposure time, which was assumed on the basis of average travel times by coach bus and long-distance train. The remaining components affect the final result to a marginal extent.

The fully open nature of the developed method and the possibility of selecting up-to-date scientific data on the probabilities of transmission of pathogens of any type, as well as the current stage of epidemic, mean that it can be utilitarianly used in monitoring and managing epidemic risk in transport. Currently, transport policy and development strategies must take into account epidemic aspects, especially in the case of mobility in large urban agglomerations. This is not only a matter of passenger safety but also of the responsibility and role of transport processes in the spread of the epidemic. The author developed and presented a fully complementary methodology to assess epidemic risk in transport for the example of the SARS-CoV-2 virus pandemic, which was described in (Burdzik, 2022). This methodology is fully prepared for implementation in transport policy and in transit managers and operators.

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