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STUDY ON THE ESTIMATION OF SARS-CoV-2 VIRUS PATHOGENS' TRANSMISSION PROBABILITIES FOR DIFFERENT PUBLIC BUS TRANSPORT SERVICE SCENARIOS

Summary. The worldwide COVID-19 pandemic revealed societal challenges, with passenger transport rapidly experiencing the impacts of the virus and the evolution of the concept of safety in transport. Evaluating the likelihood of viral transmission within transportation systems may be a substantial challenge, considering the complex processes that influence the incidence of random transmission events. This paper introduces a method for determining the probability of pathogen transmission in public transport, focusing on the SARS-CoV-2 virus. The study draws on scenarios from the first and second waves of the COVID-19 pandemic in Poland, a period that was devastatingly marked by the lack of available vaccines. This study aims to add value to the scientific community by offering an estimation of the likelihood of SARS-CoV-2 transmission in public transport and a preliminary risk assessment for COVID-19 infection, considering the number of active, non-isolated COVID-19 cases in the Polish population. The potential of this approach was demonstrated through a comparison between two different categories of passenger transport in a city bus. Based on the presented case study and the calculated probability of pathogen transmission, it is estimated that the probability of SARS-CoV-2 infection during the second wave of the COVID-19 pandemic in Poland through the use of public transport was approximately 0.05%. Probability estimations based on elementary events, which can vary depending on the service category (for instance, the form of ticket purchase, availability of seating or standing places, or ticket inspection), can reveal even the smallest differences in the total likelihood of pathogen transmission. However, these minute individual variations significantly impact the total metrics calculated for daily users of public transport. For effective monitoring of potential epidemic threats and for designing suitable interventions and restrictions to lower the risk of future pandemics, it may be necessary to understand the role that transportation systems, particularly public transport systems, play in the spread of pathogens.

1. INTRODUCTION

One of the greatest threats to civilization has been and will be epidemics, which, due to the rate of spread and serious effects, turn into global pandemics. Human history shows several cases of such pandemics, which had drastic consequences and caused the deaths of huge human populations. Examples that come to mind most quickly are the plague and the Spanish flu. Unfortunately, one of the allies of the spread of the epidemic is transport, which determines the mobility of people, enabling them

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to move quickly over considerable distances. It also significantly hinders the fight against epidemics and the identification of outbreaks.

These were the main factors responsible for the rapid spread of the SARS-CoV-2 virus epidemic. Despite advancements in medicine, improved personal hygiene, universal access to medicine and medical care, and the rapid flow of information, the pace and scope of the spread of the epidemic resulted in the COVID-19 pandemic, which began in 2020. This is why the role of transport in monitoring epidemic outbreaks, managing epidemic risk, and preventing and fighting epidemics is so important. The key factor in risk assessment is the likelihood of hazards occurring. For epidemic risk, this is the probability of transmission of virus pathogens. In the case of a human-to-human virus, human-to-human contact is key to the spread of the virus, and public collective transport becomes critical in this approach.

Transport significantly affects the spread of epidemics, with COVID-19's swift proliferation partly attributed to hypermobility and global urbanization [1]. Particularly in urban agglomerations, public transit strategies may need to prioritize limiting disease spread [2]. A mathematical model for HIV virus dynamics showcases how public awareness and behavior impact infections [3]. Lessons about SARS-CoV-2 and COVID-19 were quickly learned [4], affecting not just health risks but also service performance, financial viability, social equity, and sustainable mobility [5]. Domestic travel restrictions' impact on COVID-19's spread in Japan has been studied [6], with global scientists exploring risk assessments [7-10].

Risk perception, the instinctive evaluation of hazard exposure [11], informs risk-taking behavior and has been studied across various travel modes [12]. Modes that confine passengers are risky, as contaminated surfaces can lead to the spread of viruses [13-14]. The pandemic is expected to influence future urban planning [15], as COVID-19 has severely affected urban life and public transport usage [1], prompting a need for sustainable transport models [16]. A study in Istanbul revealed a significant post-pandemic reduction in public transport usage frequency [17].

Meeting safe public transport demands and government restrictions often involves capacity reduction without a clear methodological basis. The transmission probability in public transport should be a key measure for epidemic safety actions and controlling the spread of viruses [18]. Research quantifying spread parameters in urban districts has confirmed the role of transport in the spread of diseases [19]. A survey in Bangladesh indicated a high perceived risk of COVID-19 transmission in various travel modes, with buses being the riskiest mode of transportation [11].

According to an analysis of the entire transport sector that operated during the pandemic, the expectations of customers in terms of transport safety have changed dramatically. Interestingly, this issue applies not only to passenger transport but also to freight transport, in which the importance of safety was not only related to damage to shipments but also to the potential contamination of surfaces. Undoubtedly, however, these expectations have changed the most in passenger transport, especially collective transport. Passengers require epidemic safety because the awareness of the threats of viral infection has increased significantly; some people even became obsessive in the initial phase. Currently, the whole world is trying to get over the feeling of the ubiquitous epidemic threats, while the awareness of these threats will forever remain in the heads of the generations affected by the COVID-19 pandemic. Therefore, passengers' expectations regarding transport safety include epidemic safety.

The main contributions of the results presented in this paper are a quantitative estimation of the probability of pathogen transmission when traveling by public transport, together with the identification of all mechanisms of potential pathogen transfer during the transport process. The research question defined before the analytical experiments was, "How can all mechanisms of pathogen transmission that occur during travel in public transport be taken into account?" This paper presents estimates of SARS-CoV-2 transmission probability in public bus transport, following the methods detailed in [2]. It is an original and comprehensive methodology for estimating the probability of transmission of droplet and contact virus pathogens, which considers all transfer mechanisms as single independent events. This method is fully original, and this paper represents the first time it has been applied in this field.

The structure of this paper is as follows. An introduction emphasizes the importance of the SARS-CoV-2 virus pandemic for health and social life—in particular for mobility and public transport. This is followed by a section on the synthesis of the state of knowledge in the field of pathogen transmission and estimating the probability of infection in which the method used in the paper is briefly described.

The next section is devoted to a case study using the described method for estimating the probability of transmission of pathogens for different scenarios of travel in public bus transport. Finally, a summary describes the results obtained and potential areas of application of the presented method.

2. ESTIMATION OF THE PROBABILITY OF PATHOGEN TRANSMISSION

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 [20].

The role of fomites has been questioned [24], and initial data supporting fomite transmission was contested in a July 2020 study [25]. The Centers for Disease Control and Prevention (CDC) affirmed the possibility of infection through contact with contaminated surfaces but deemed the risk to be low [26]. Increasing evidence indicates that the respiratory route is the predominant mode of transmission for SARS-CoV-2 [27]. Quantitative microbial risk assessments indicate a less than one in 10,000 chance of contracting SARS-CoV-2 through fomites or secondary transmission [28]. Nonetheless, a comprehensive analysis of potential transmission mechanisms must incorporate the risk from fomites, even if it is minimal.

Public transportation vehicles are regarded as significant contributors to the spread of COVID-19 [29]. Numerous studies over the past three years have assessed infection risk in transport, primarily focusing on airborne virus spread. However, this focus neglects to fully assess the risk of infection and largely overlooks surface contamination as a secondary infection source. Therefore, the authors propose the following research objectives:

- Evaluate studies on the infection probability for single events, such as touching a contaminated surface,
- Identify the sequence of events by which pathogen transmission could occur (e.g., respiratory droplets, surface contact, and person-to-person contact), and
- Estimate the cumulative probabilities of pathogen transmission, considering various combinations of events in the transportation process.

A literature review on safety research [30] revealed that most studies rely on basic descriptive statistics and scientometric mapping tools. As detailed in [2] and exemplified in Smart Cities transport services in [21], the deep hazard identification (DHI) method can be employed to identify and preliminarily assess epidemic threats in transportation. This method involves a process-oriented approach and analysis of events featuring possible pathogen transmission. Consequently, a complete sequence of events is established, each potentially contributing to pathogen spread, along with a comprehensive mathematical formula to estimate cumulative probability.

Assumptions related to travel time, distance, contact surfaces, and regulations were made for public transport. After identifying all potential virus transmission events in the mapped processes, independent events can be assigned probabilities based on a literature review. The final step involves estimating the total probability of pathogen transmission for a specific transport service. A comprehensive explanation of this method for estimating viral transmission probability in transportation can be found in [2].

When estimating the probability of pathogen transmission using the theory of the sum of elementary events, it's crucial to identify all independent events where pathogen transmission might occur. These events might involve respiratory droplets, skin contact through touching another person, or contact with a fomite. Therefore, a thorough analysis of the entire event sequence should be conducted, considering all potential virus transmission routes (Fig. 1).

A potential limitation of the method used here is the possibility that some activities are not independent, forming clusters with varying probabilities or networks of conditionally linked events. In such cases, alternative probability calculation methods, such as conditional probability, the Bernoulli scheme, or Bayesian networks, should be considered.

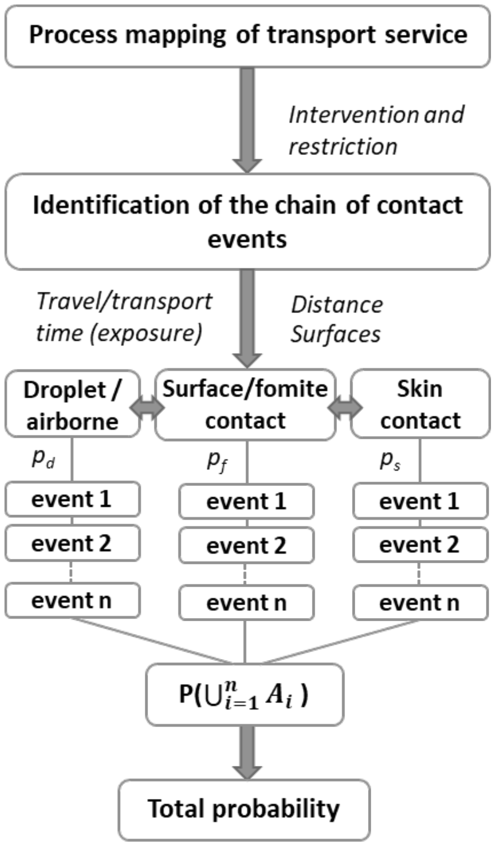

Fig. 1. Algorithm of the methodology for estimating the total probability of viral pathogen transmission in transport processes [2]

The method developed and the corresponding estimated values refer to the probabilities of pathogen transmission and not the probability or risk of infection. An accurate estimation of infection likelihood necessitates an examination of factors such as the proportion of virus (pathogen) carriers in the population and the specific characteristics of the population's immune system, which may vary based on factors such as age or vaccination status.

3. STUDY ON THE ESTIMATION OF SARS-CoV-2 VIRUS PATHOGENS' TRANSMISSION PROBABILITIES FOR DIFFERENT VARIANTS OF PUBLIC BUS TRANSPORT SERVICES

Public transport is assumed to be collective and is provided to a large group of passengers. One of the main goal in collective public transport management is to increase the efficiency of means of transport, especially in large cities. Solutions offer to increase efficiency of means of transport can reduce the harmful effects of transport, such as the effects of fuel combustion in the engine, noise and vibrations, and reduce the phenomenon of transport congestion, which extends the travel time and increase the time of exposure to emission factors. These are the indisputable advantages of collective transport in relation to individual transport and, taking into account the above advantages, the right direction for the development of transport systems. However, two key aspects have changed since 2020, namely passengers' safety and the risk of viral infection.

This risk strongly depends on the probability of the transmission of virus pathogens, which, in turn, depends on the operations taken during transport and the organization of passenger flow. Thus, an innovative and original methodology for estimating the probability of pathogen transmission in transport was developed [2]. The proposed method is universal and open, and it allows input data to be freely selected depending on the current epidemic situation, the number of infected people, virus reproductive rates, the effectiveness of preventive measures (e.g., protective masks and vaccinations), and current epidemic restrictions. In the case of public transport, the type of means of transport, organization of transport (e.g., limiting the number of passengers and the allocation of seats), the use of additional security devices (e.g., shields and filters), procedures related to vehicle disinfection, etc., may also have an impact on the probability of transmission of pathogens. Therefore, the open formula of the developed method is its great advantage and allows it to be adapted depending on the case under consideration. It is also recommended to precede the probability estimation and carry out the assessment of epidemic threats in accordance with the DHI (deep hazard identification) method [21].

This study investigates public transportation during the most critical phase of the COVID-19 pandemic in Poland, specifically during the second wave. The likelihood of virus transmission is intrinsically tied to the prevalence of the virus within a population. Per the data obtained from the Ministry of Health on November 30, 2020, accounting for the first and second wave, a total of 990,811 confirmed cases had been reported in Poland since the pandemic began. This figure approximates to 2.6% of the Polish population. On the same day, the number of active cases was 396,147, roughly equating to 1.04% of the population.

The number of active cases covers all people who are infected at the same time. These confirmed cases represent individuals who are currently hospitalized or in quarantine. It can be noted that these numbers include individuals who were confirmed positive a few days and even a few weeks prior. As these values overlap, it is evident that November 2020 was an exceptionally challenging month in Poland, with the highest volume of active cases reported daily during that period.

Nonetheless, the possibility of undetected cases within the population should not be disregarded. A study by researchers from the University of Warsaw [31] estimated that the ratio of undiagnosed to diagnosed cases is 5.6 to 1. This ratio could significantly change depending on the phase of the pandemic. Thus, the actual number of infected individuals may potentially exceed the confirmed cases by a factor of more than five.

Viral diffusion can be more conducive in an enclosed environment than open. The direct detection of pathogens in the air or on surfaces is exceedingly challenging. With regard to public transportation, it would be optimal to have a clear understanding of safety parameters. The study presented in [32] provides insights into the air circulation and frequently touched surfaces within a city bus during routine operation. This information may improve the understanding of potential virus transmission routes and the efficacy of implemented protective measures.

Fig. 2 provides a schematic of a city bus's interior, illustrating restrictions related to seating and standing positions during the initial waves of the COVID-19 pandemic. The right side of Fig. 2 highlights surfaces potentially implicated in pathogen transmission. The middle area of Fig. 2 depicts the locations of two filters used in the air circulation analysis. For a comprehensive air circulation assessment, the influence of airflow from open windows and doors should also be considered.

Airborne transmission is a key factor in SARS-CoV-2 infection. Computational fluid dynamics allow this transmission to be studied in urban buses. A Lagrangian approach has been used to evaluate the impact of roof-top HVAC (heating, ventilation, air conditioning) on droplet transmission from sneezing and coughing, while the Eulerian tracer method allows the modeling of aerosol transmission from breathing and talking [33]. Fig. 3 depicts results from these simulations in a typical city bus (47 m^3, 40 seats, and space for ~20 standing passengers), illustrating particle positions post-sneeze (21 sec), post-cough (9 sec), and concentration of exhaled air after 20 minutes.

Mapping public transport processes from a passenger's perspective helps identify stages when pathogen transfer may occur (Fig. 4). Factors such as close contact with others and touching skin or surfaces (e.g., handles, ticket validators) must be considered in varying transport service scenarios. According to data and tables from [2], each identified transmission mechanism within these processes was assigned a probability value. The values used in this study may be criticized and adapted according to a specific context, and they are merely used as illustrative of the approach used.

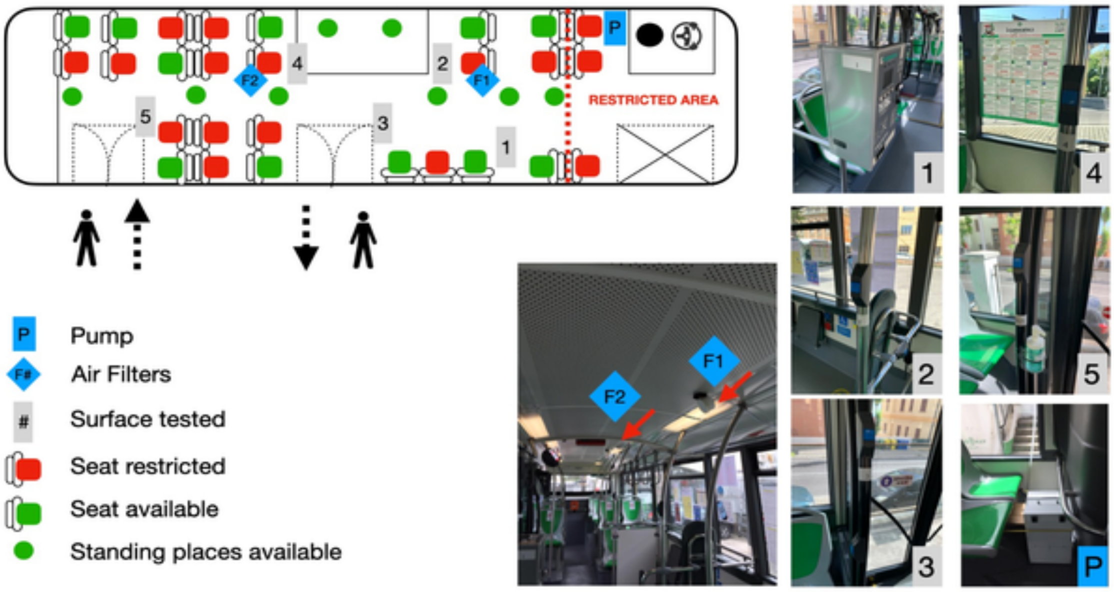

Fig. 2. Top view of a cross-section of a public transport bus with marked places where the transmission mechanism of SARS-CoV-2 virus pathogens may occur [32] (© 2020 Di Carlo et al.)

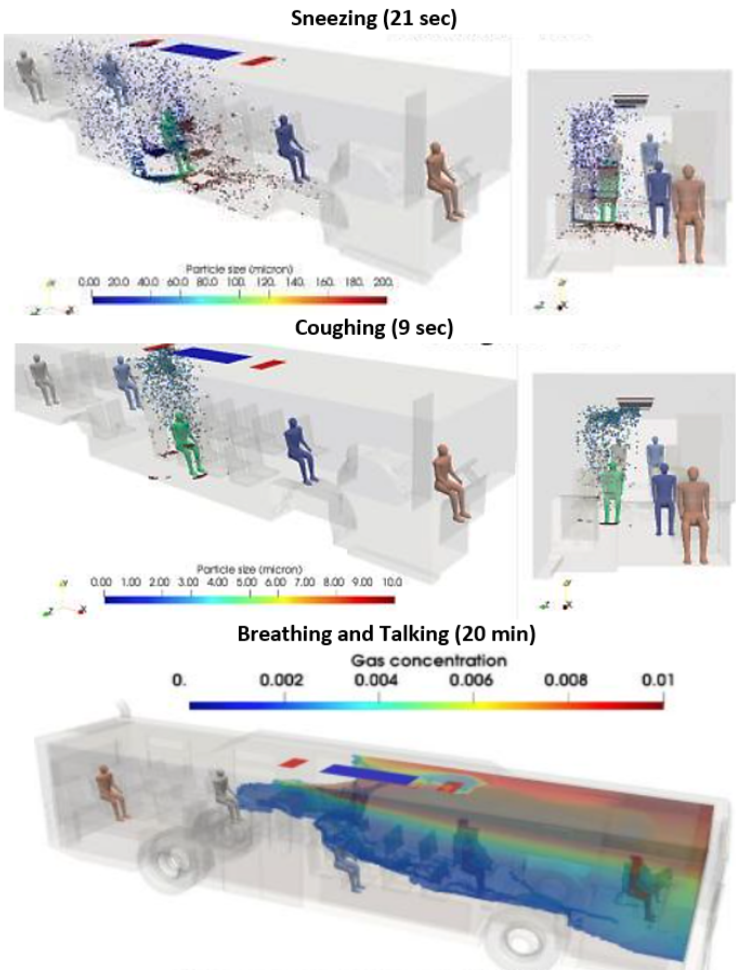

Fig. 3. Illustration of the simulation of the airborne transmission of a virus in a city bus for the cases of sneezing, coughing, and talking (and breathing) [33] (© 2022 Ramajo et al.)

An analysis of urban passenger flows estimates that the average bus or tram journey time is 25 minutes, with intervals between stops typically ranging from five to 15 minutes. This helps determine exposure time during transit. The risk of transmission was adjusted according to the legislation requiring face masks in public transport during the study.

The determinants of transmission depend on transport activities. Four scenarios of service implementation from a passenger's perspective were distinguished:

- The passenger purchases a ticket via a mobile app and takes a seat.
- The pssenger purchases a ticket via a mobile app and remains standing.
- The passenger purchases a ticket at a kiosk or from the driver and takes a seat.
- The passenger purchases a ticket at a kiosk or from the driver and remains standing.

Each scenario possesses distinct pathogen transfer opportunities, affecting the overall transmission probability. Factors such as ticket control during transit and mask-wearing were also considered.

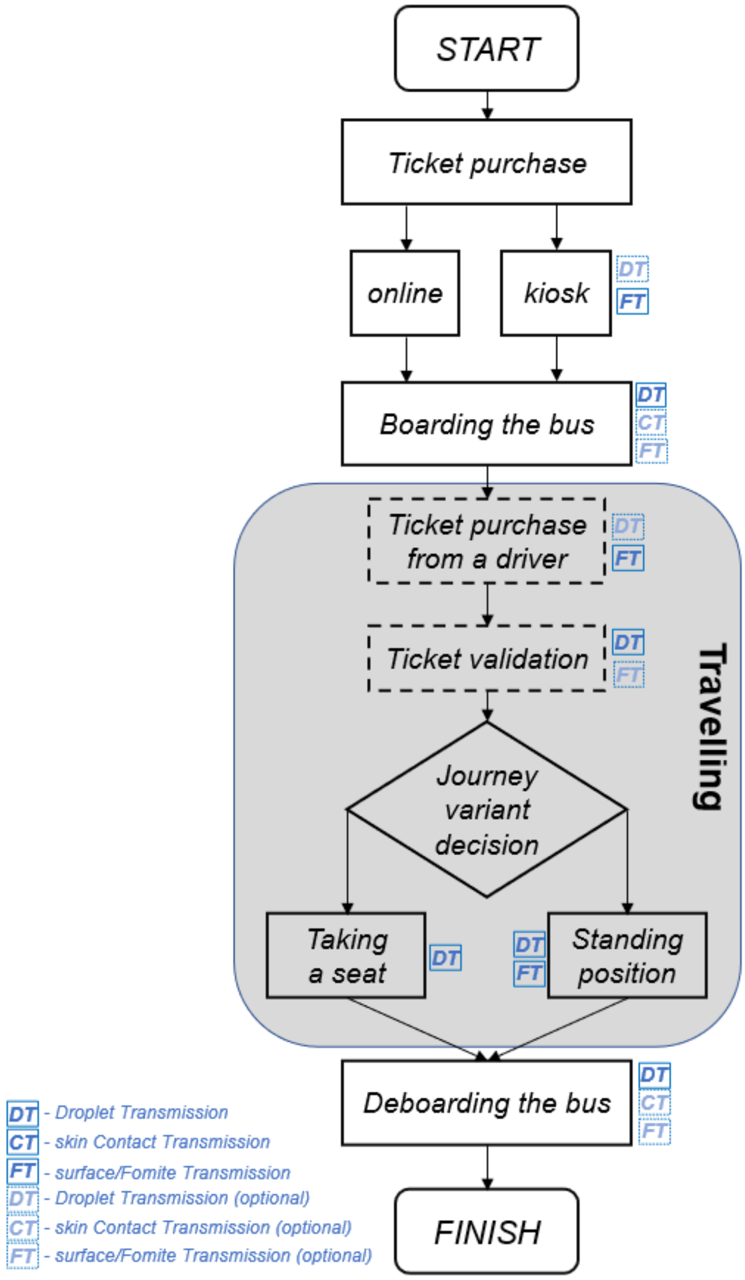

Fig. 4. Flowchart of passengers traveling by bus public transport with the potential mechanism of virus transmission

This paper contrasts two scenarios: In Scenario 1, a passenger buys a ticket via a mobile app and sits during transit. In Scenario 2, a passenger purchases a ticket at a stationary kiosk or from the driver and stands and holds onto a handle during the journey. Scenario 2 also includes personal ticket validation by a controller, adding to the risk during ticket purchase and validation. In Scenario 1, contact with handles or railings is eliminated if the passenger is seated. However, in Scenario 2, the risk from such contact must be considered. Tables 1 and 2 present the probabilities of elementary events in public transport for Scenarios 1 and 2, respectively. It is assumed that all passengers wear masks and that the bus capacity is capped at 50% to reflect pandemic conditions.

Table 1

Probabilities of elementary events occurring by means of collective public transport (Scenario 1)

Event	**Infection route**	**Event index**	**Probability of event $P(A_i)$**	**$1-P(A_i)$**
Ticket purchase	*Eliminated*		-----	-----
Boarding	Contact	A_1	0.0001	0.9999
	Droplet	A_2	0.0039	0.9961
Ticket validation	*Eliminated*		-----	-----
Traveling	Contact *eliminated*		-----	-----
	Droplet	A_3	0.0441	0.9559
Deboarding	Contact	A_4	0.0001	0.9999
	Droplet	A_5	0.0039	0.9961

Table 2

Probabilities of elementary events occurring by means of collective public transport (Scenario 2)

Event	**Infection route**	**Event index**	**Probability of event $P(A_i)$**	**$1-P(A_i)$**
Ticket purchase	Contact	A_1	0.0001	0.9999
Boarding	Contact	A_2	0.0001	0.9999
	Droplet	A_3	0.0039	0.9961
Ticket validation	Contact	A_4	0.0001	0.9999
	Droplet	A_5	0.00082	0.99918
Traveling	Contact	A_6	0.0001	0.9999
	Droplet	A_7	0.0441	0.9559
Deboarding	Contact	A_8	0.0001	0.9999
	Droplet	A_9	0.0039	0.9961

The calculation procedure involves a multi-stage calculation of the sum of the probabilities of independent (individual) events. In the case of an operation in the process during which several pathogen transmission mechanisms may occur (e.g., in Tab. 1 - Boarding: Contact and Droplet), the sum of the probability of these events is calculated first. At this stage, the probability values for the sums of all elementary events assigned to subsequent activities in the infection route are obtained. Then, in the next calculation stage, the total probability is calculated as the probability of the sum of elementary events from Stage 1.

Next, following the adopted computational procedure, the following values are calculated one by one:

a) Scenario 1:

$P(A_1 \text{ u } A_2) = 1 - 0.999*0.9961 = 0.0040$,

$P(A_3) = 0.0441$,
$P(A_4 \text{ u } A_5) = 1 – 0.999*0.9961 = 0.0040$.

The cumulative probability of pathogen transmission is determined by summing the probabilities of individual events, as represented in the following equation:

$P_p = 1 – (1\text{-}0.0040)\cdot(1\text{-}0.0441)\cdot(1\text{-}0.0040) =$ **<u>0.0517</u>** (**<u>5.17%</u>**).

b) Scenario 2:
$P(A_1) = 0.0001$,
$P(A_2 \text{ u } A_3) = 1 – 0.999*0.9961 = 0.0040$,
$P(A_4 \text{ u } A_5) = 1 – 0.999*0.99918 = 0.00092$,
$P(A_6 \text{ u } A_7) = 1 – 0.999*0.95588 = 0.04421$,
$P(A_8 \text{ u } A_9) = 1 – 0.999*0.\ 9961 = 0.\ 0040$.

The cumulative probability of pathogen transmission is determined by summing the probabilities of individual events, as represented in the following equation:
$P_p = 1 – (1\text{-}0.0001)\cdot(1\text{-}0.0040)\cdot(1\text{-}0.00092)\cdot(1\text{-}0.04421)\cdot(1\text{-}0.0040) =$ **<u>0.052855</u>** (**<u>5.286%</u>**).

The probability of pathogen transmission is not equivalent to the probability of viral infection. The probability resulting from the number of active infections in the population must be considered to determine the general probability of viral infection attributable to the provision of transport services. Therefore, the overall probability of viral infection can be primarily evaluated using the following equation:

$$P_i = P_p \cdot R_{ac}, \tag{1}$$

where:
P_p – probability of pathogen transmission and
R_{ac} – quotient of the total number of active cases to the size of the population.

Other infection risk factors, such as individual immunity, vaccinations, and additional prevention (gloves, disinfection, and social distancing), should also be considered.

According to previously mentioned estimates, the values regarding active cases should be adjusted to account for undiagnosed active cases (e.g., using a conversion factor of five). For instance, in November 2020, which marked the peak of the second wave of COVID-19 in Poland and the onset of the most severe epidemic situation since the start of the pandemic, the proportion of active COVID-19 cases to the total population of Poland was 0.622%. However, considering the dynamics and development trend of the epidemic at that time, this proportion may be simplified and assumed to be 1%. This assumption enables us to estimate the initial probability of viral infection, which represents the infection risk when using public transport. Based on the data, the general probability of SARS-CoV-2 infection in public transport may be estimated as follows:
$P_i = 0.0517\cdot0.01 = 0.000517$ (0.0517%) – Scenario 1,
$P_i = 0.05286\cdot0.01 = 0.0005286$ (0.0529%) – Scenario 2.

These estimates suggest that the infection risk while using public transport during the peak of the COVID-19 pandemic in Poland was around 0.05%, assuming a 1% prevalence of infection among individuals who were not quarantined and could use public transportation.

The obtained results were validated through a comparison with research presented in the literature. The paper [33] presents the results of the calculation for different quantum emission rates and operation conditions by application of the Wells-Riley model for virus spreading in public buses. The calculation results carried out for the case of a 25-minute travel and strongly depend on the parameters of the droplet transmission model. If we assume the following parameters important for the transmission of droplets in the air, such as: quantum emission amount of 125 g/h, air flow rate of 1 m^3/s and air exchange of 75% and that passengers wear protective masks, the estimated probability is below 1%. However, if we assume that the quantum emission is 58 g/h, the air flow rate is 1 m^3/s and there is a complete lack of air exchange in the vehicle and that the passengers aren't wearing protective masks, the probability may be more than 12%.

The paper [34] presents the results of *in situ* research. The selected surfaces on different devices in buses and subway trains and air samples were PCR-tested for the presence of the SARS-CoV-2 virus pathogen. The presence of traces of RNA of the virus was confirmed in 30 of 82 cases examined on laboratory samples. The tested samples were collected from 58 surface swabs, 9 air conditioning filters, 3 air conditioning dust samples, and 12 samples of ambient air, all taken from buses and subway trains operating in Barcelona between May and July 2020. Based on the experimental results, the authors [34] presented the modeling of in-bus infection probability. In this study, the average probability of infection and individual infectious risk for an exposure time of 15 minutes for people susceptible to speaking or breathing was between 0.01% (when fresh air was provided at a volume of 850 m^3/h) to 0.09% (when no fresh air was provided).

The paper [35] presents a study on the prediction of the contagious risk of SARS-CoV-2 virus infection in buses via the respiratory tract. It was assumed that the passengers are in close proximity, and the Euler-Lagrangian model was used to analyze the dispersion of respiratory particles, which represents the relationship between the generation of droplets during breathing and speaking by an infected person (emitter) and the absorption of these droplets by the susceptible/exposed person (receiver). This model assumes the case of mutual orientation of people face to face and the absence of excessive air fluctuations in the immediate vicinity. In the studies presented in [35], it was assumed that the travel time of passengers in an urban bus was 24 minutes, and that passengers breathe and talk during the travel. The average values of airborne transmission risk (probability) for one infected subject (emitter) breathing or speaking were 0.48 (breathing, windows closed) and 2.1 (speaking, windows closed).

A mutual comparison of these results confirms the reality of the obtained results. It is difficult to find research results that cover the methodology presented in this paper, considering boarding the bus, ticket purchase and control, and distinguishing whether the passenger travels sitting or standing.

The method for estimating the likelihood of pathogen transmission proposed in [2] is based on the probability of the sum of elementary events. This allows probabilities to be distinguished depending on the scenario of the transport service. Although differences may seem small, for the two scenarios presented, the differences are 0.116% for pathogen transmission and 0.0012% for the risk of infection. These small percentages become significantly impactful when considering the scale and number of passengers using public transportation daily.

4. CONCLUSIONS

Constant challenges in public transport include economic aspects, including fuel consumption [36], ecological aspects, and safety. In the aspect of safety after 2020, epidemic risks should be taken into account. Estimating the likelihood of SARS-CoV-2 virus transmission is not equivalent to estimating the likelihood of contracting COVID-19. The likelihood of viral infection depends on factors such as the proportion of carriers in the population and the specific characteristics of the population's immune system, which can vary based on age and vaccination status. The probability of contracting COVID-19 and its complications is influenced by individual characteristics and the immune system, even in the case of confirmed viral infection. However, estimating the probability of SARS-CoV-2 transmission is considered a reliable measure of infection risk, as it can be assessed based on objective determinants of pathogen transmission.

This paper presents a case study focusing on public transport during the most critical stage of the COVID-19 pandemic in Poland, specifically the second wave.

Ongoing monitoring and periodic risk assessments are essential in addressing epidemic threats [21, 22]. It is also important to carefully consider measures aimed at reducing the risk of epidemic spread [23].

The present article demonstrates the application of a method for estimating the probability of pathogen transmission in public transport using SARS-CoV-2 as a case study. The approach utilizes a probability calculation assuming independent events, illustrating potential mechanisms of viral infection during the use of public transport. The approach provides flexibility in updating results based on different contexts, such as varying transportation services, viruses, and epidemic stages. It requires pathogen transmission probability databases to be updated for specific cases being investigated.

A case study was presented for two different scenarios of public transport services to highlight the advantages of the proposed method for estimating pathogen transmission likelihood. These scenarios differ in terms of ticket purchase methods, seated or standing travel, and additional activity resulting from personal ticket control. Probability estimation was conducted considering pandemic restrictions, such as mask mandates and limited bus capacity.

Based on the case study and the calculated probability of pathogen transmission, it was estimated that the probability of SARS-CoV-2 infection during the second wave of the COVID-19 pandemic in Poland due to using public transport was approximately 0.05%. This estimation considers a number of assumptions of non-isolated virus carriers, along with several assumptions mentioned in the text.

Furthermore, this article demonstrates the proposed method's sensitivity to differences in transport service scenarios through the presented case study. Although the individual differences in the cases studied may be small, considering the scale and number of passengers using public transport daily and the impact on the speed and range of epidemic spread, especially in large cities, these differences can lead to a significant number of potential infections. This highlights the method's advantages in estimating pathogen transmission probability for different passenger transit scenarios in public transport, contributing to enhancing epidemic safety in transportation.

The significance of this paper lies more in the proposed approach and its explicit mathematical formalism than in the derived estimations. This allows the method to be adapted to other contexts. Further research and refinements may be necessary to develop this into a more practical risk assessment tool.

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