

Analysis of the boarding and disembarking process time on the example of the Pesa 122NaB tram operated in the city of Bydgoszcz

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Highlights:

1. Study of boarding and disembarking time of a tram operated in a medium-sized city.
2. The passenger flow in public transport significantly affects the travel time.
3. Passenger flow time can be approximated by a linear function.
4. Passengers move faster when there are more of them.

Summary: The processes of boarding and disembarking passengers in public transport significantly affect travel time. As a part of sustainable urban development, it is necessary to implement new techniques to streamline traffic and promptly respond to the public transport passengers' demand for efficient movement around the city. The structural solutions used in tram and bus vestibule areas are constantly changing to speed up these processes. Understanding passenger behaviors is a necessary element in optimizing passenger flow between the stop and the rail vehicle, as well as within the vehicle itself. However, there is a lack of data that could be used to evaluate specific solutions. The article measured boarding and disembarking times from a Pesa 122NaB tram example operated in the city of Bydgoszcz, which has a population of approximately 340,500 residents. Due to the city's functioning specificity, the analysis of passenger flow in trams differs from that in metropolitan areas with over a million residents because tram journeys in cities of this size occur on longer routes than in metropolitan transport, which results from the lack of alternatives to tram transport. Most analyses are conducted within metropolitan transport, where the dynamics of passenger flow will be significantly different than in medium-sized cities. This study analyzed a specific case where the district served by the tram line under analysis – Fordon – is separated from the city, generating a greater number of long-distance journeys. The study recorded 106 boarding and 126 disembarking instances from the tram. The studies were preliminary as part of a development project for an AI platform enabling real-time passenger flow analysis. The article analyzes the frequency of passenger numbers occurrence. The average passenger flow time was approximated by a linear function $R^2 = 0.94$. The time per person decreased with the number of passengers; it ranged from 1 to 1.5 seconds for 5 or more passengers. The presented data can be used for further comparative analysis of passenger flow processes, both for the proposed AI algorithm and for analytical purposes for rail vehicle manufacturers and municipal public transport operators.

Key words: passenger flow, vestibules; public transport; train design

1. Introduction

Public transport plays a very important role in urbanized areas. Current trends toward a sustainable transport system include various means of transport that have to exist on the limited infrastructure [1,2]. Public transport provides the opportunity to move around for people who do not have or do not want to use their vehicles daily [3,4]. Urban transport should ensure accessibility [5], the comfort of travel [6,7], the number of connections [8], competitive costs [9,10], and, above all, safety [11]. The mentioned aspects have been the subject of research in many scientific papers. The boarding and disembarking processes in public transportation significantly impact the travel

time between stops [12,13]. Implementing new techniques to streamline traffic and promptly respond to the public transport passengers' needs for efficient movement within the city is essential for sustainable urban development [14,15].

The exchange of passengers on trams is an extremely significant component of urban transportation systems, impacting their efficiency and the comfort of travel for all users. This process primarily occurs at stops, where passengers have the opportunity to board or alight from vehicles, thereby creating space for new travelers. Effective organization of passenger exchanges is crucial for maintaining traffic flow and reducing travel time, translating into passenger comfort and satisfaction. To ensure an attractive and high-quality service, it is essential to avoid overcrowding situations. Overcrowding can lead to passenger discomfort and hinder movement within the vehicle, which can be particularly problematic during peak hours. Therefore, it is important to ensure appropriate vehicle provision and to minimize the risk of overcrowding through proper schedule planning and fleet adaptation to flowing passenger needs.

Furthermore, for the efficient operation of the urban transportation system and cost optimization, it is also essential to reduce the number of underutilized vehicles. Utilizing underutilized vehicles can lead to financial waste and excessive energy consumption. Therefore, transportation companies must continually strive to optimize their fleets and adjust them to the actual demand for transportation services in a city. Increasingly, optimization of the utilization of transport company assets is carried out using AI tools [16,17].

The structural solutions employed in the tram and bus vestibule areas undergo continuous changes to accelerate these processes. Understanding passenger behaviors is crucial for optimizing passenger flow between the stop and the rail vehicle, as well as within the vehicle itself [18,19]. However, there is a lack of data available for evaluating specific solutions.

Due to the specific characteristics of how Bydgoszcz functions, the analysis of passenger flow on trams differs from that in metropolitan areas with populations exceeding one million [20]. This disparity arises because tram journeys in cities of such size occur over longer distances than in metropolitan transit, owing to the absence of alternatives to tram transport. Most analyses are conducted within metropolitan transit, where the dynamics of passenger flow significantly differ. This study examines a particular case where the district served by the analyzed tram line – Fordon – is distinctly separated from the city, resulting in a greater number of long-distance journeys [21,22].

Literature review

Podolski analyzed the information about the time lost during a stop depending on the number of boarding and disembarkation people in 1985 [23]. The average remains 1,2 second to get on the tram and 1 second to get off. The time of stopping by tram at the stop, according to data from the 1980s, is on average 15 seconds, and very rarely this time was shorter than 8 seconds. The above results must be considered in the context of tram types, which is typical in Poland in the 80s, high-floor trams.

One of the ways to reduce the waiting time at stops is to use the advanced public transport systems (APTS), part of the Intelligent transportation system (ITS). The APTS is equipped with

automatic fare collection (AFC) systems usable for forecasting passenger flow in global terms. The AFC enables to count the number of passengers boarding and disembarkation [24,25], but not the time of the boarding and disembarking process. The main factor in estimating passenger flow is tram stop time. It is possible to use the AFC systems not only to count passengers but also to count the time from the start to the end of disembarkation and boarding. Guo et al. proposed a model that combines cost theory (CT) and automatic frequency control (AFC) in passenger flow prediction [26]. The AFC was used to predict passenger flows by Zou et al. in metro stations [27]. Samaras et al. described the BusGrid information system for the improvement of productivity and customer service in public transport bus services, which included a passenger counting module generating a passenger flow module [28].

Normally, passenger flows are linear. However, in hard conditions like an overflow of trams, eventually, bad weather conditions, could change conditions drastically and make them nonlinear. Sometimes, the ITS systems are equipped with modules analyzing more non-linear factors. It could be e. g. an artificial neural network (ANN) or a support vector machine (SVM) [29]. In the context of passenger flow, the ANNs can be used to model and predict the movement of people through transportation hubs such as airports, train stations, or bus terminals [30]. By analyzing historical data on passenger behavior, the ANNs can identify patterns and make predictions about future passenger flow. Pekel and Kara used the ANN models in their research on public transport in Istanbul [31]. Özuysal et al. and Wang et al. used the ANN models to estimate passenger flow in light rail transit (LRT) [32,33].

The other way of predicting passenger flow is the Poisson model [29]. It is a statistical model using a discrete probability distribution that models the number of events occurring in a fixed interval of time or space, given the average rate at which the events occur. The Poisson model can be used to predict the number of passengers who will arrive at a particular location within a given period, based on the historical data on passenger arrivals. An application of the Poisson model was performed by Zhou et al. at the Airport Security [34]. Zhai et al. applied this model in the bus networks [24].

Zhao et al. proposed a non-linear model for predicting the rate of passenger flows in a transit system to analyze tendencies in the turbulent flow of passengers [35]. They carried out the research in Liaoyuan City (Jilin Province, China). Wei et al. analyzed statistics of passenger flow by forecasting with the help of an empirical mode decomposition and the back-propagation neural networks (EMD- BPN) method [36]. In some publications [37,38], the use of long short-term memory (LSTM) by using matrices of passenger flow was proposed. The passenger flow data are typically sequential, with each data point representing the number of passengers passing through a particular location at a given time. The LSTM networks can process this sequential data and capture the temporal dependencies between successive data points. Baghbani et al. proposed to use of a bus network graph convolutional long short-term memory (BNG-ConvLSTM) [25]. The BNG-ConvLSTM is a deep learning model architecture designed for video-based human action recognition. It combines two different neural network components: the convolutional neural networks (CNNs) and the long short-term memory (LSTM) networks. Feng et al. proposed a new method to predict passenger flows in a large comprehensive transportation hub in

the Guangzhou metropolitan area with the Transformer method, which was about 88,57% effective, and the other method FC-LSTM was 82.23% effective [39]. Li et al. proposed a model, in which passengers board only by first (single) door. It was a typical model for suburban transport, in which drivers sell tickets [40]. It made obstruction in the front vestibule area. As a part of their paper, Nagaraj et al. proposed using the LSTM and the Recurrent Neural Network (RNN) algorithms to analyze passenger flow using deep learning [41]. Their dataset included parameters such as a bus id, a bus type, a source, a destination, and passenger counts, which are processed using the greedy layer-wise algorithm. Yildiz et al. analyzed the boarding procedure based on a new seat layout on the airplane [42]. The researchers described topics of vestibule layout and communication routes.

The boarding and disembarking process time analysis can be used to compare different tram or bus vestibule designs with each other. The analysis of such comparisons would enable the identification of key design solutions and it would allow a better and more conscious design. However, there is a lack of data on individual models of trams that would allow such a comparison. In the paper, the boarding and disembarking process time on the example of the Pesa 122NaB tram operated in the city of Bydgoszcz was investigated. The analogy between the behavior of passengers and fluids was used to determine the primary dependence usable to the vestibule designs comparison.

2. Materials and Methods

During the investigation, the boarding and disembarking processes time was measured. The boarding time is defined as the period from the moment the doors begin to open until the completion of boarding, i.e., when the last passenger is stably standing inside the vehicle/on the platform. The passenger flow rate measurements were carried out on all stops on tram line 5 in Bydgoszcz in February 2023. The measurements were performed on the 122NaB trams produced by the PESA Bydgoszcz SA. There were two factors studied – the number of passengers and the time of boarding and disembarkation. Passengers were counted by organoleptic method both from inside and outside of the tram. Time was measured by stopwatch with an accuracy of 0.001 s. The results of time measuring were approximated to 0.5 s. Passengers were counted always by flow through one double door. 106 measurements of boarding and 129 of disembarking were made. Measurements were also recorded for people with disabilities, people with strollers, and others.

According to the World Population Review [43], the estimated population of Bydgoszcz is 340,500. According to the Bydgoszcz Information Center [44], almost 500,000 passengers use public transport daily in Bydgoszcz. The tram system length is a total of 41,4 km. The track gauge in Bydgoszcz is 1000 mm. The runner-up in the tram line by the length in Bydgoszcz is number 5: Rycerska – Łoskoń. It has a length of 18,2 km. This line connects the most important places in the city – a railway station, the city center, a bus station, malls, universities, and the biggest district of Bydgoszcz - Fordon. According to the official city website, about 20% of citizens live in Fordon. A schema of Bydgoszcz's tram lines is presented in Figure 1.

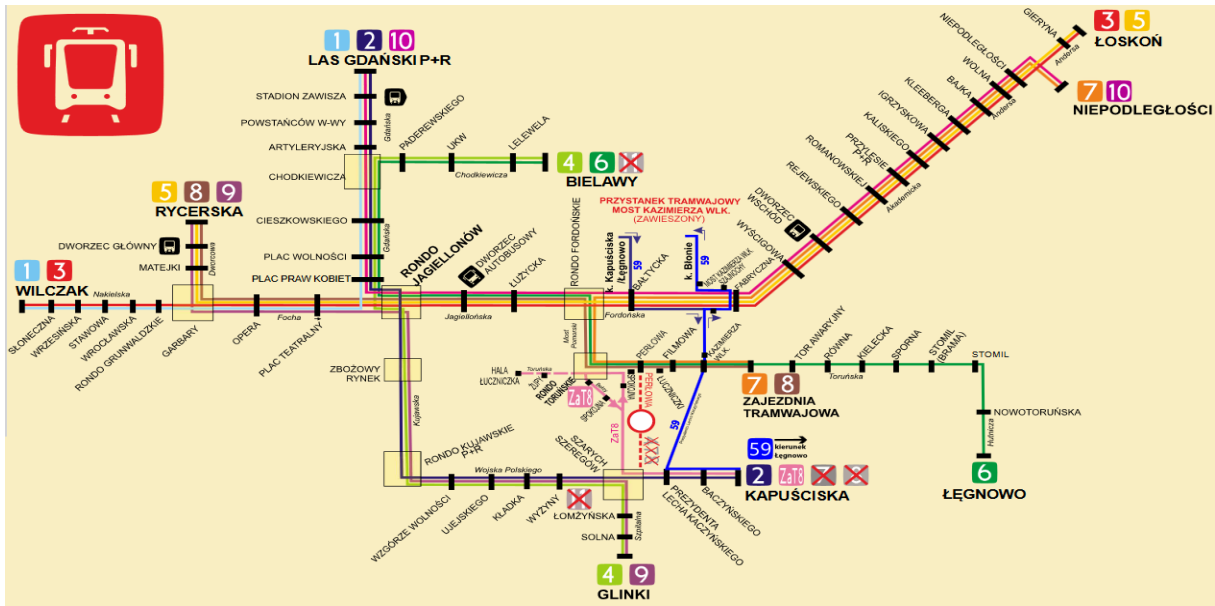


Fig. 1. A scheme of Bydgoszcz city tram lines [45]

People can travel by two types of trams on line 5: the 805Na type and the 122NaB type – Pesa Swing. According to Urban Transport Enthusiasts Club [46], “805Na is a high-floor tram manufactured in Poland from 1979 to 1992 in workshops Konstal Chorzow”. Currently, the Bydgoszcz’s Public Transportation Company is replacing them and introducing the 122NaB-20 trams. The 122NaB tram series is equipped with 5 cars with a total of 40 chairs and a potential capacity of about 207 people. 100% of the floor in the passenger segment is low-floor. The tram is 30 m long and 2,35 m wide. Interior transitions between seats are over 660 mm in width. The maximum speed is 70 km/h. The 122NaB type is also equipped with an air conditioning system, a wheelchair place, video surveillance, a ticket machine, WiFi, and USB chargers. The 122NaB tram is shown in Figure 2. A double-door area of the Pesa 122NaB tram is shown.



Fig. 2. A space on the tram near the double doors

The flow analogy

The process of passenger movement in public transport vehicles is often referred to as a flow. This analogy accurately describes the way people move and it can be used to analyze the traffic in public transport vehicles such as trams, trains, and buses. It can also be taken literally as it is shown by Petrouš et al. [29]. One of the primal principles in the fluid mechanics is the Bernoulli's principle, which can be represented as an equation:

$$e = \frac{p}{\rho} + \frac{v^2}{2} + g \cdot z \quad (1)$$

where e is the specific energy [J/kg], p is the fluid pressure [Pa], ρ is the fluid density [kg/m³], v is the fluid mean velocity [m/s], g is the acceleration due to gravity [m/s²] and z is the elevation of the point above a reference plane [m].

Bernoulli's equation is the energy equation. The first term of the equation (p/ρ) is internal energy. The second term of the equation ($v^2/2$) is kinetic energy, and the third term of the equation ($g \cdot z$) is potential energy. This equation describes the fluid flow, it but can be also used to describe the process of boarding and disembarking passengers on the train.

In this analogy, the internal energy will depend on the number of passengers in the vehicle, the vehicle structure, and random factors affecting vehicle throughput. The kinetic energy should be equated with the speed or time of embarkation and disembarkation of passengers. The potential energy should be identified as the number of embarking or disembarking passengers.

The Bernoulli equation is an energy equation and it satisfies the principle of conservation of energy. Therefore, this equation can be presented in the form:

$$\frac{v^2}{2} + g \cdot z = C_1 \quad (2)$$

$$v^2 = -2 \cdot g \cdot z + C_2 \quad (3)$$

An analogy to the boarding and disembarking process can be written:

$$t = A \cdot n + B + C \quad (4)$$

where C_1 and C_2 are constants, t is the total embarkation or disembarkation time [s], n is the number of passengers embarking or disembarking, the value A is the sum of factors dependent on the number of passing passengers, the value B does not depend on the number of passengers and it represents a constant dependency on the model of the operated tram, the value C is optional and it depends on the presence of disabled people.

A detailed description of the elements affecting the value of factor A is:

$$A = A_1 + A_2 + A_3 \quad (5)$$

where A_1 is a factor depends on the time required to open the doors to a width that allows disembarkation; A_2 is a factor depends on dependent on the equipment with a device (button) for passengers to open the doors – whether it allows opening before the vehicle stops, its reaction time if activated only after stopping, and its sensitivity; A_3 is a factor depends on the on the speed of passengers and their reaction to external stimuli.

On the other hand, factor B is the sum of the following constants:

$$B = B_1 + B_2 + B_3 + B_4 + B_5 \quad (6)$$

Factors B_1 to B_5 are the functions of certain measurable values. Factors B_1 to B_3 depend on the distance between critical nodal points significant for the study. Further, B_1 is the height difference between the platform and the tram, B_2 is the distance from the tram's entrance threshold to the platform edge, B_3 is the width of the entrance. Factor B_4 is based on the size of the city, which generates a demographic distribution (gender and age) of residents using public transportation. Factor B_5 is the ticket distribution system – the use of paper tickets, the presence of validators, and ticket machines in the entry area. The last factor is the most complex to analyze, as it requires an analysis of flow for given geometric values of the vehicle. Here, the flow time would depend on the flow pressure.

In the tram's entry area, passenger movement was observed to be laminar. Depending on the time of day, and thus the traffic intensity, it was noticeable that during peak hours, passenger movement becomes turbulent after entering the tram. In contrast, during off-peak hours and at terminal stops, movement within the tram was more laminar. For studies with an accuracy of up to 0.5 seconds, the number of passengers did not impact the analysis of passenger flows. However, using higher accuracy in AI-based analysis algorithms, it is possible to detect differences dependent on traffic intensity.

In our opinion, the analysis of this simple relationship between boarding/disembarkation time and the number of passengers can be a benchmark when considering interior designs for public transport vehicles. Interior design is the only element that can improve passenger flow within the station.

3. Results and discussion

3.1. Number of passengers

During the experiments, 106 times getting on the tram and 126 times getting off the tram were recorded. The number of recorded cases for different numbers of passengers for the boarding process is presented in Figure 3 and for the disembarkation process in Figure 4. The number of passengers is a very important factor. It affects not only the way of designing vestibules in public transport vehicles but also the way of designing stops [29].

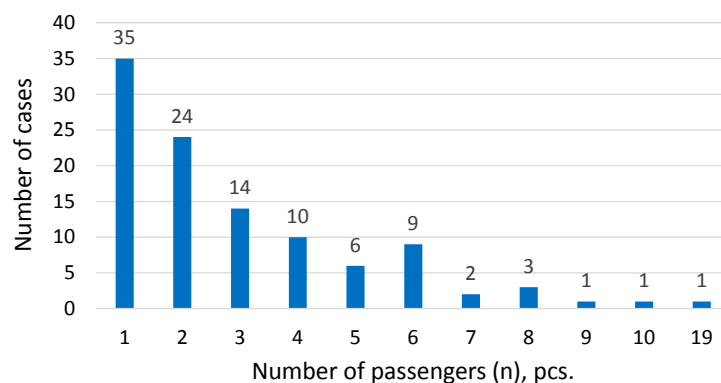


Fig. 3. The number of recorded cases vs. the number of passengers boarding the tram

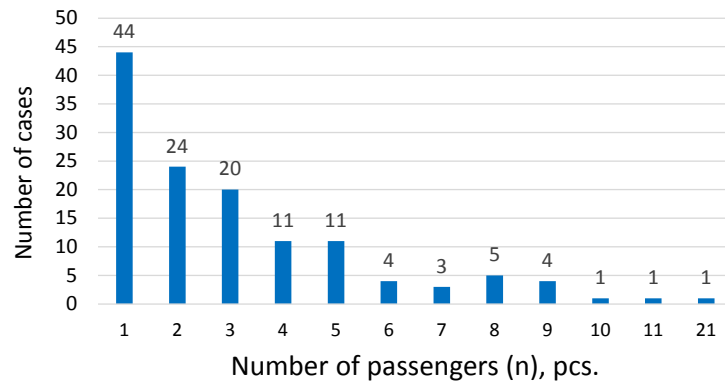


Fig. 4. The number of recorded cases vs. the number of passengers disembarking the tram

Among the registered cases over 50% involved one or two persons, and 80% of all cases involved five passengers or fewer. More than 10 passengers were observed only three times. Therefore, the number of passengers getting on and off the tram, through one entrance, was small. Even though the measurements took place during peak hours. The reason for this is the small size of the city (the population of Bydgoszcz is approx. 340 500 citizens), the appropriate design of stops (passengers get on and off evenly through all tram doors), and the properly selected size of trams.

In the case of larger cities, the number of passengers getting on and off through the doors of the tram or other means of public transport will probably be higher. However, the authors failed to find data on this topic.

3.2. Mean time to get on and off

Figure 5 presents the mean boarding time depending on the number of boarding passengers. Figure 6 presents the mean disembarking time depending on the number of disembarking passengers. Additionally, the standard deviation of measurements is marked in Figure 5 and Figure 6 for cases, where the number of measurements was greater than 1 (Figure 3 and Figure 4).

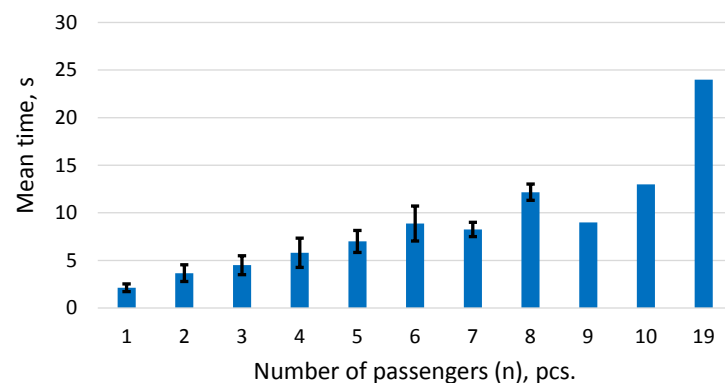


Fig. 5. The mean time of boarding vs. the number of passengers

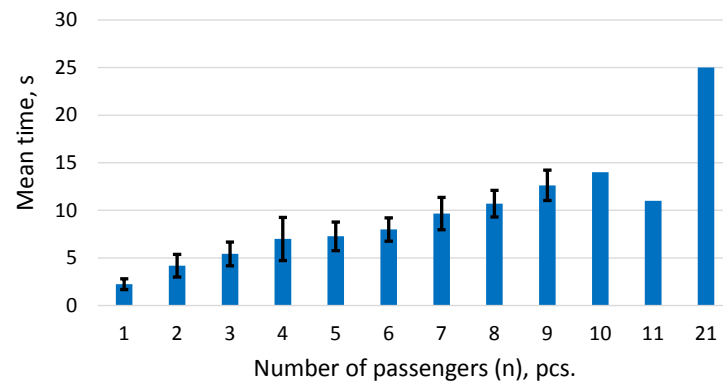


Fig. 6. The mean time of disembarking vs. the number of passengers

The mean time of boarding or disembarking was higher with the increase in passenger numbers. The exception to this rule was the time of boarding for 7 and 10 passengers (Figure 5) and the time of disembarking for 11 passengers (Figure 6), but the number of recorded cases was equal to 1 or 2 (Figure 3 and Figure 4). For this reason, these times cannot be considered authoritative. There was no consistent relationship between the number of passengers and the standard deviation. However, the lowest standard deviation was observed in the case of 1 passenger, and the highest was observed in the case of 4 boarding passengers, and for 4 to 6 disembarking passengers. It can be concluded that the process of boarding and disembarking one person has the lowest standard deviation, as it is undisturbed by the presence of other people. Obtaining the highest value of the standard deviation in the area of 4 to 6 passengers is unclear. This may be due to sociological reasons [47,48] or it may be accidental. It would be necessary to increase the number of measured times to confirm that it is not just that.

The data from Figure 5 and Figure 6 are approximated and presented in Figure 7. The mean time of boarding and disembarking processes can be approximated by the linear function $t = 1.2692 \cdot n$ with $R^2 = 0.9439$ as it is shown in Figure 7 or as a function $t = 1.1309 \cdot n + 1.4537$ with $R^2 = 0.9656$ according to Eq. (4). The boarding and disembarking processes' mean times were similar for the number of passengers lower than 7. This was an area where the number of recorded cases was significant, and the data can be considered statistically representative. However, the obtained R^2 parameter was higher than 0.9, even with all the data included. Both of the designated approximation functions indicate that the dependence between the number of passengers and the time of boarding and disembarking processes is linear. Sołtysiak et al. analyzed bus stops in Bydgoszcz as the ratio of the number of passengers to the passenger exchange time – regardless of whether passengers were boarding or disembarking [49]. The dependence was also linear but the coefficient of determination was $R^2 = 0.79$.

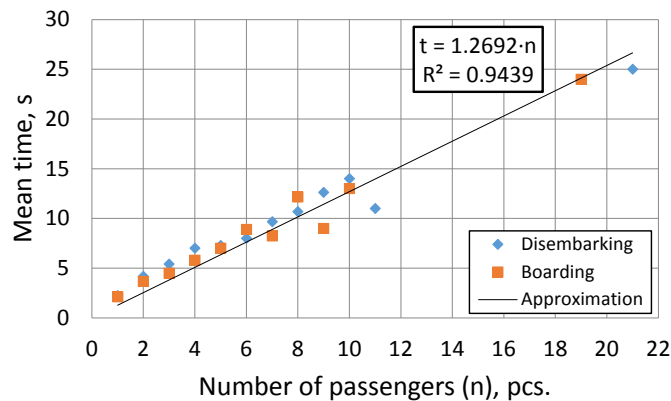


Fig. 7. Approximation of the boarding and disembarking processes meantime

The mean time of boarding and disembarking processes per person is depicted in Figure 8. The highest time was obtained for 1 person and then decreased up to a value oscillating between 1 and 1.5 s, which was obtained for 6 or more passengers. The lowest value was obtained for 9 boarding passengers and 11 disembarking passengers. The decrease in time per person with the number of passengers was caused by the fact, that people do not get on and off individually, but together, carrying out the process to some extent independently of each other. However, the speed of people and the throughput of the door (whether 1, 2, or 3 people pass through the door at the same time) have their limitations. For this reason, the value of the time per person will always be greater than zero, but it will tend to a specific number, specific for a given construction solution. For the investigated tram (Pesa 122NaB), this time oscillated in the range of 1 to 1.5 s.

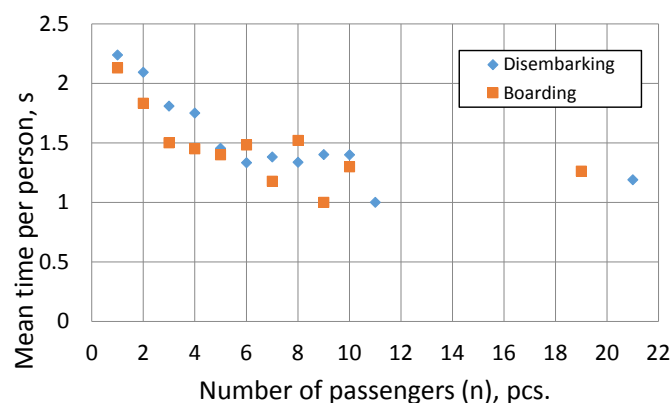


Fig. 8. The boarding and disembarking processes time per person vs. number of passengers

The disembarking time per person was generally higher than the boarding time, except for time for 6 and 8 passengers. It can be caused by the fact that normally the disembarking process is realized before the boarding process and during this time, the passengers have time to approach the tram door and position themselves around it. It should also be investigated how such positioning affects the extension of disembarkation time. However, this issue does not concern the design of the tram, but the design of the tram stop.

3.3. Subsequent research steps

The presented investigation was the first step in creating a methodology enabling the comparison of vehicles' vestibule structures. The next step of the project is creating an application based on artificial intelligence (AI) algorithms, which will allow us to automate the process of counting boarding and disembarking people and measuring the boarding and disembarking time. The use of the AI algorithm will speed up the investigation and it will allow to analyse of the larger data sets. The application is under creation and its operation algorithm is shown in Figure 9.

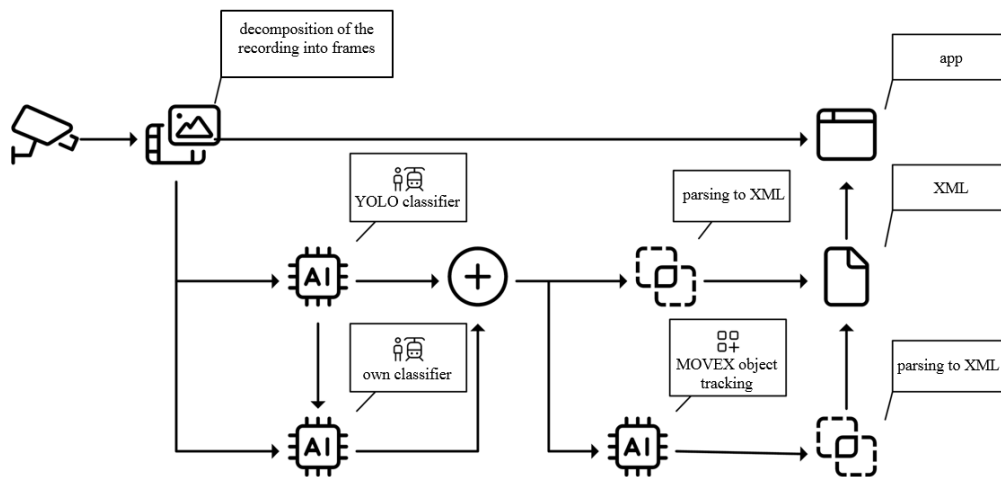


Fig. 9. A structure of the AI algorithm

Additionally, it is planned to compare the flow of passengers through the tram with the flow of fluid through a channel of similar geometry into the interior of the vehicle. For this purpose, the flow of passengers through the tram will be recorded using a camera placed on the ceiling of the vehicle. The passenger movement path will be compared to a streamline. The passenger movement path will also be determined using the AI algorithm. This part of the investigation will be an extension of the analogy presented in section 3 of this article.

Based on the above research, a methodology for comparative analysis of vestibule structures in terms of passenger flow will be proposed. This will enable more conscious and efficient design of vestibules and entire vehicles.

4. Conclusions

In the article, the time of boarding and disembarking processes were analyzed in the example of the Pesa 122NaB tram. The measurements were carried out in Bydgoszcz city in Poland. The mean time of these processes can be approximated by the linear function with a high coefficient of determination $R^2 > 0.9$. The obtained function can be used to compare the time of boarding and disembarking processes with the other tram. It is possible to compare the effectiveness and usefulness of the construction solutions of tram vestibules or other public transport vehicles based on the analysis of the approximation function for the average time.

It was shown that the average time per person of the boarding and disembarking process decreased with the number of passengers and above 5 passengers the time per person did not change and oscillated between 1 and 1.5 s.

The presented data can be used for further comparative analyses concerning boarding and disembarking processes, comparative analysis of structural solutions of tram vestibules, and others. Subsequent research steps were presented.

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