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STUDY ON THE IMPACT OF SINGLE-LEAF DOOR DESIGN IN TRAMS ON THE RATE OF PASSENGER EXCHANGE

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Abstract: *This paper addresses the design of side-door systems in tram vehicles with regard to achieving the highest possible passenger throughput. It is a well-known fact that in the rail vehicle design process, the primary criterion determining the number of doors is the expectations of the operator ordering the vehicles. This article analyzes whether the use of single-leaf doors at the rear of a single-ended tram has a positive effect on efficient passenger exchange at stops. The analysis is based on data obtained from recordings of passenger flows captured using a drone and an action camera in Polish cities characterized by medium and high levels of passenger turnover. The analysis is further supported by the use of a YOLOv10s convolutional neural network. The conclusions drawn from this study may contribute to changes in the way tender requirements for new tram vehicles are formulated in cities.*

Keywords: Public transport, Tram design, Passenger flow, Artificial intelligence, YOLO, Data analysis

1. Introduction

Effective planning of public transport operations in cities represents a significant challenge in transport engineering. Example studies (Du et al., 2025; Liu et al., 2025) show that successful planning of pedestrian movement directions requires both detailed analyses and strategic thinking, often supported by object-tracking techniques based on artificial intelligence.

Tram design constitutes a specific subfield—indeed, almost a separate branch—of rail vehicle engineering, as it relies more heavily on adapting the vehicle to local conditions and the client's requirements than is the case for passenger railway vehicles. This results naturally from operation on dedicated networks that differ between cities in terms of track gauge, supply voltage, and other distinguishing factors. In contrast, railway vehicles are subject to a higher level of standardization, for example through Technical Specifications for Interoperability (TSIs) (European Commission, 2014).

For tram vehicles, guidance is provided by Regulation No. 107 (United Nations Economic Commission for Europe, 2015). This regulation specifies only a minimum of two doors and a maximum distance of 7 m to an emergency exit from any passenger-accessible area of the vehicle. In practice, compliance with these requirements typically leads to door spacing of approximately 5–6 m, considering a standard vehicle width of about 2.0–2.5 m. At the tram ends, these guidelines must be adapted to the interior layout. The ends of the vehicle may contain driver's cabs in bidirectional trams or gondola-type end sections in single-unit trams. Consequently, in both multi-unit and single-unit trams, a portion of the space otherwise available to passengers is allocated to staff areas or seating.

This engineering task therefore constitutes a dual-domain challenge. From the perspective of transport engineering on the client's side, it is necessary to assess how many vehicle entrances are realistically

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required. From the mechanical engineering perspective, the vehicle must be designed to meet both safe evacuation requirements and the client's expectations regarding the usable floor area in the passenger compartment. This issue represents the core problem addressed in this article. The study analyzes whether the use of single-leaf doors at the ends of trams is advantageous from a passenger-flow perspective. Preliminary observations from passenger-flow studies indicate the formation of bottlenecks near single-leaf end doors when these are the closest doors to the platform entrance.

2. Materials and Methods

The tram boarding and alighting process was examined based on video footage recorded with a DJI Air 3 Fly More Combo (RC-N2) drone and a GoPro 13 HERO action camera. The drone's positioning and the mounting location of the action camera (using a magnetic mount) were adapted to the specific recording site and tram stop. The equipment was arranged to avoid obstructing the tram doors, to capture as many doors as possible within the field of view, and to maintain a recording angle between 45 and 90 degrees. The research was conducted based on the methodology described in more detail in (Szyca et al., 2025, Szyca et al., 2026).

The recordings were made in 4 cities in Poland, the data on the measurement points is presented in Tab. 1. The total number of analysed recordings was 200. For each city 50 measurements.

Tab. 1: Data on the measurement

City	Number of inhabitants	Name of tram stop	Hours of recordings	Types of operating trams
Bydgoszcz	324.000	Rondo Jagiellonów	1-3 p.m.	122NaB, 121NaB, 122N
Gdańsk	488.000	Galeria Bałtycka 02	8-10 a.m.	122NaG, 128NG, N8C-NF. NGT6
Katowice	278.000 (2.500.000 in Silesian Conurbation)	Katowice Rondo	1-3 p.m.	19T, 105NWr, LF 07AC. MF 17AC, MF 19AC, MF 24AC
Wrocław	670.000	Wrocław Dworzec Główny	7-9 a.m.	105Na, 105N (mod.), 116Nd, 2012N, 2017N, 146N, HF 11AC

Stops in all analyzed locations are situated in the strict city centres and generate some of the highest passenger flows in these cities. The stops in Katowice and Wrocław have an open layout, allowing access from multiple directions. In contrast, the stops in Gdańsk and Bydgoszcz have only a single functional entrance. This situation made it possible to verify the occurrence of passenger accumulation near the last doors of a given tram set through a comparative analysis of stop layouts.

3. Results and discussion

As can be observed in Fig. 1, under specific boundary conditions a phenomenon of passenger accumulation occurs in the area of the vehicle's last door, when this door serves as the last boarding entrance. Fig. 2 illustrates the mechanism by which this phenomenon occurs. Studies have shown that the average passenger exchange time at a stop ranges between 15 and 30 seconds, depending on the level of occupancy of both the tram and the stop. In the case of the stops Gdańsk – Galeria Bałtycka and Bydgoszcz – Rondo Jagiellonów, dwell times approximately 5 seconds longer were recorded under comparable tram and stop occupancy conditions. This is indirectly reflected in the measurement results presented in Tab 2. which presents the analysis results for individual cities. A clear difference can be observed between Gdańsk and Bydgoszcz, where the stops have a single access point, in contrast to Katowice and Wrocław, where there are multiple access points to the stop from different directions.

Fig. 1: Screenshot from a recording made in Gdańsk during measurements conducted in 2024 at the Galeria Bałtycka stop

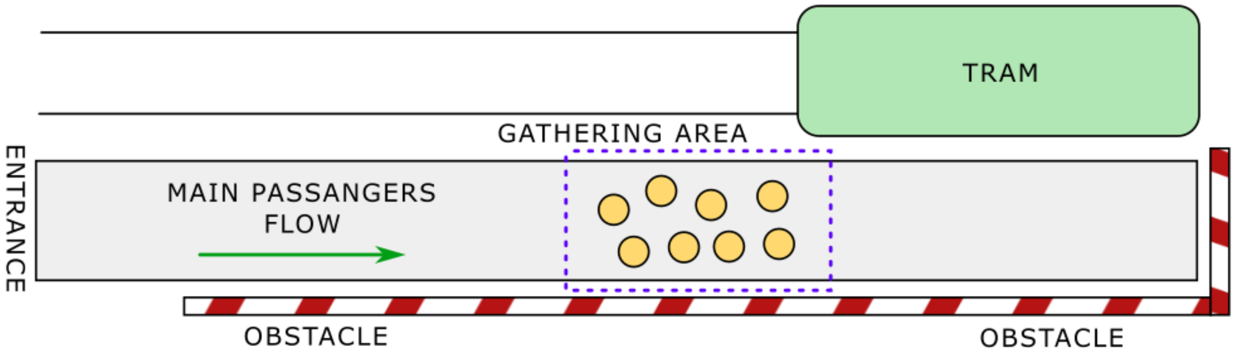

Fig. 2: Visualization of passenger flow conditions at the stop Rondo Jagiellonów (Bydgoszcz) and partially at Galeria Bałtycka (Gdańsk)

Tab. 2: Data on the measurement; Measurement results marked as Type A – cases in which passenger exchange through the last door lasted the longest and could have extended the tram dwell time; Type B – cases in which, due to an insufficient number of passengers waiting at the stop, passenger exchange through the last door did not take place; Type C – cases in which passenger exchange through the last door did not last the longest.

City	Type A	Type B	Type C
Bydgoszcz	88%	0%	12%
Gdańsk	44%	36%	20%
Katowice	4%	20%	76%
Wrocław	2%	12%	86%

4. Conclusions

The conducted observations and measurement data showed that trams equipped with single-leaf doors at the ends of the vehicle exhibited a lower capacity for smooth passenger exchange at stops. This phenomenon is particularly evident when a platform has only one functional access point, or when the stop is located in the vicinity of a company or institution that naturally generates significant passenger flows, forcing boarding to occur at the front or rear of the vehicle. The analyses demonstrated that when the above-mentioned factors accumulate, trams experienced dwell times longer by at least 5 s in more than 50% of cases.

Even very small-time savings achieved at the level of individual stops can, at the scale of the entire public transport system, lead to noticeable operational effects. To illustrate this phenomenon, a hypothetical example of a tram line serving a route consisting of 20 stops can be considered. Assuming that at 50% of them, i.e. at 10 stops, organizational or infrastructural improvements allow the dwell time or running time to be reduced by 5 s, the total time saving per single trip amounts to 50 s.

Although this value may appear negligible at the level of an individual run, its significance increases with the number of services operated. Assuming that one vehicle performs 30 trips per day, which is typical for an intensively operated tram line, the daily time saving per tram equals 1500 s, i.e. 25 min. For a line operated by 10 vehicles, this translates into 250 min, or approximately 4 h 10 min of cumulative time savings per day across the system.

This effect becomes even more pronounced over a longer time horizon. On an annual scale, assuming operation over 365 days, this results in approximately 1520 h of saved operational time. When converted to a standard 8-hour working day, this corresponds to the equivalent of approximately 190 working days, or more than 60 days of continuous vehicle operation. Such a substantial value does not result from a single, capital-intensive investment, but from the systematic elimination of minor time losses recurring multiple times throughout the day.

From the perspective of a public transport authority, such micro-level time savings can be utilized in several ways. They may increase schedule slack, improving punctuality and system resilience to disruptions, enable reductions in travel times perceptible to passengers, or—in the longer term—lead to optimization of the number of vehicles required to operate a given line. This example demonstrates that even improvements measured in individual seconds can generate significant benefits at the scale of an entire transport system.

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