CETRA2026 27-30 May 2026, Bol, Island Brač, Croatia
9th International Conference on Road and Rail Infrastructure

MITIGATING TRAM BUNCHING AND ENHANCING HEADWAY UNIFORMITY USING AN INNOVATIVE SERVICE: A SIMULATION-BASED CASE STUDY IN ZAGREB

Hrvoje Haramina[1], Jasna Blašković Zavada[1], Marko Slavulj[1], Adrian Wagner[2]
[1]*University of Zagreb, Faculty of Transport and Traffic Sciences, Croatia*
[2]*University of Applied Sciences St. Pölten, Carl Ritter von Ghega Institute for Integrated Mobility Research, Austria*

Abstract

The phenomena of tram bunching can be caused by numerous factors and significantly contribute to the reduction of transport service quality in public urban transport, primarily because passengers at stops are required to wait for an inappropriately long time for the next tram or travel in overcrowded vehicles. Within the scope of this research, a solution has been proposed to mitigate service quality degradation caused by extended passenger waiting times and reduce the probability of tram bunching occurrence on a defined section of the tram network in Zagreb (Croatia) where they most significantly affect the quality of transport service. Considering actual data regarding the occurrence of bunching, a section of the Zagreb city tram network on the route between terminal Prečko, Savski Gaj rotor, Zagrepčanka and Sveučilišna aleja stops, including the Savski most terminal, was selected as the area for a case study. The paper proposes an innovative solution for enhancing the quality of transport service in the observed tram traffic area by redistribution of tram vehicles among different tram lines, which involves the introduction of a new tram service on the route between the Prečko and Savski most terminal. This control method is primarily intended to reduce the occurrence of excessively long headways between trams of currently existing services operating in that area, mostly caused by their uneven arrival in the observed part of the network or by already established bunching. For the purpose of evaluating the proposed solution, an infrastructure model of the observed tram network section is developed. This model is used to perform a simulation analysis of tram traffic for several typical traffic scenarios from a real-world environment in which the mentioned problem occurs. The simulation experiments analyzed various operational scenarios for the improvement of tram service, assessing its effectiveness in standardizing headways and mitigating service quality degradation caused by extended passenger waiting times and the potential onset of bunching.

Keywords: tram bunching, headway optimization, public transport, Zagreb, urban rail system modelling

1 Introduction

Tram bunching is a phenomenon in which two or more trams operating on the same route, originally scheduled to be evenly spaced, end up arriving at a stop simultaneously. This creates a cluster of vehicles followed by a long gap in service, disrupting the intended headways and consequently increasing passenger waiting times. This phenomenon generates a negative feedback loop in which the leading vehicle becomes overcrowded and slower, while the following vehicle is underutilized and gradually catches up with the first one.

As a result, passenger transport services become inefficient, and passenger loads are distributed unevenly among vehicles. Common causes of bunching include uneven passenger demand, traffic congestion, and stochastic dwell times. Uneven passenger demand occurs when a slight delay causes more passengers to accumulate at a stop. The increased number of passengers results in longer boarding times, which further delays the vehicle and creates a negative feedback loop. Traffic congestion represents another important factor, as trams often share road space with cars, which can cause unpredictable delays and disrupt the regular spacing between vehicles. Stochastic dwell times refer to random variations in the time required for passengers to board or alight from a tram. These variations accumulate over time and contribute to irregular service intervals. The problem of vehicle bunching in public transport systems has been the subject of intensive scientific research since the mid-twentieth century. Given that trams in many cases operate on the same road infrastructure as cars, it can be concluded that trams exhibit similar bunching dynamics as buses and can therefore be analyzed using the same methods for quantifying headway variability. The theoretical foundation was established by Newell (1964), who mathematically demonstrated that a public transport system operating with fixed headways is inherently unstable, meaning that any small delay tends to grow exponentially if no external corrective measures are applied [1].
Contemporary literature treats the bunching phenomenon as a problem of system dynamics. Daganzo (2009) introduced the concept of headway-based dynamic control, suggesting that vehicles should not strictly follow a fixed timetable but instead adjust their operation according to the position of the vehicles ahead and behind them [2]. This method, tested in cities such as Barcelona, has demonstrated a significant reduction in passenger waiting time variance. A significant portion of the global literature focuses on Transit Signal Priority (TSP) systems [3, 4]. Gardner et al. (2018) analyzed tram systems in Lyon and Zürich and concluded that active signal priority at intersections not only accelerates tram operations but also represents an important mechanism for breaking up vehicle clusters. This is achieved by allowing the leading vehicle to pass intersections more quickly while intentionally delaying the following vehicle with a red signal to restore the desired headway [4]. Although global models are applicable, the Zagreb tram system has certain specific characteristics. Šipuš (2017) notes that, unlike systems in Western Europe (such as those in Vienna), the Zagreb network experiences a high level of interaction with individual motorized traffic on critical corridors [5]. Unlike classical single-line bunching, this research examines scenarios in which multiple tram lines operate along the same section of the network and partially or completely overlap within the observed segment. In such cases, bunching can arise not only from the previously mentioned causes but also from the lack of coordination between two or more tram lines arriving from different directions and continuing along the same route. In these situations, the bunching effect may become amplified, or even in the absence of classical bunching, two or more trams from the same or different lines may travel for a significant portion of the route directly behind one another. In such cases, optimizing their headways in terms of uniform distribution would further improve service quality by reducing the maximum waiting time for passengers. In this paper it will be presented how this overlap of tram lines can be used for the purpose of on-line optimization of the trams headway through the dynamic exchange of vehicles between different tram lines.

2 Description of the existing situation and computer modelling of the observed tram network section

For the purposes of this study, a section of the tram network in the City of Zagreb was selected, extending from the Prečko terminus to the stations Studentski centar, Sveučilišna aleja and Savski gaj rotor, inclouding Savski most terminal. From this terminal, tracks branch toward New Zagreb up to the Savski Gaj rotor stop, terminal Prečko and toward the city centre up to the Sveučilišna aleja and Studentski centar stops (figure 1). On the section between the Prečko terminus and the Savski most terminal, the tram track is separated from road traffic and shares infrastructure only at intersections. In contrast, the section from Savski most toward the city centre runs along a roadway shared with road traffic. The section from Savski most toward New Zagreb is again physically separated from road traffic. On the observed network segment, tram lines 5 and 17 operate between Prečko and the city centre, diverging at the Zagrepčanka stop, from where they continue in different directions. Tram line 4 operates between Savski most and the city centre, while tram line 7 operates between Savski most and New Zagreb. Tram line 14 operates between the city centre and New Zagreb and passes near the Savski most terminal but does not enter it.

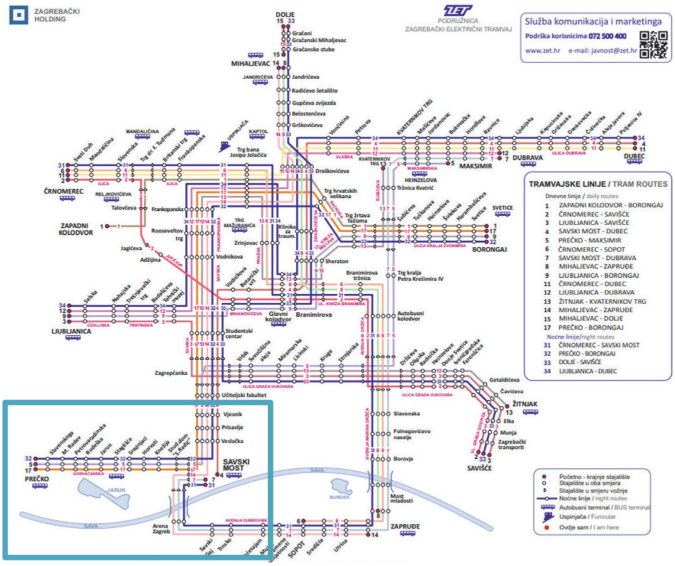

Figure 1 Tram network with the analyzed segment highlighted [6]

Rolling stock characteristics were based on the TMK 2200 tram model, which represents the standard vehicle type operating in the Zagreb tram network. For the purposes of this research, the OpenTrack simulation software was used as the primary tool for modelling and analyzing tram operations on the selected section of the Zagreb tram network. OpenTrack is a microscopic simulation tool that enables detailed modelling of rail-based transport systems, including tram and light rail networks. The software allows for the integration of key system components, including infrastructure, rolling stock, and timetable data. In this study, the infrastructure model included the analyzed section between the Prečko terminus and the Savski most terminal, with extensions toward the city center and New Zagreb. Track layout, junctions, and sections with mixed traffic operation were explicitly defined to reflect real operating conditions.

3 Mitigating tram bunching and enhancing headway uniformity using an innovative tram service

Within the framework of measures aimed at preventing and mitigating bunching, two objectives are proposed. The first objective is to maintain optimal headway between trams on the same line and between different tram lines which partly running on the same line section and prevent the accumulation of trams behind a delayed leading tram. The second objective is to reduce the excessive headway that forms in front of the delayed vehicle, which results in longer passenger waiting times and an increased number of passengers at stops due to the prolonged absence of a tram. This further affects the delayed vehicle by increasing its dwell time at stops for passenger boarding and alighting. These two objectives can be achieved by removing individual trams from lines where they operate between two vehicles with an adequate headway, and reallocating those trams to lines where the headway between vehicles is excessively long, in order to reduce it as much as possible up to a level corresponding to the minimum required headway on these lines. Within the demonstration scenario based on a real-state model of an observed part of the tram network in the City of Zagreb, the proposed strategy involves the insertion of a relief tram vehicle from the Savski most terminal, which serves as a buffer and fills the gap between to act as a buffer that fills the gap between the initial and leading tram on some line where it is needed. For this purpose, a real-time rescheduling method is applied. Selected trams operating with excessively short headways relative to the vehicles ahead and behind them are redirected to a terminal. From there, they can be dispatched at an optimal time either in one of the directions of the same tram line or reassigned to other tram lines operating in the same corridor where maintaining satisfactory headways is more critical. This method of vehicle exchange between different tram lines is inspired by operational practices used in railway systems, where locomotives are transferred from freight trains to passenger trains in cases where the original locomotive fails during the journey.

In the first phase of this simulation scenario, a problem of excessively short headway appears between trams on line 17 on the section between Prečko and Savski most. The scenario was selected based on observations of real traffic conditions using the ZET Školjka application (figure 2).

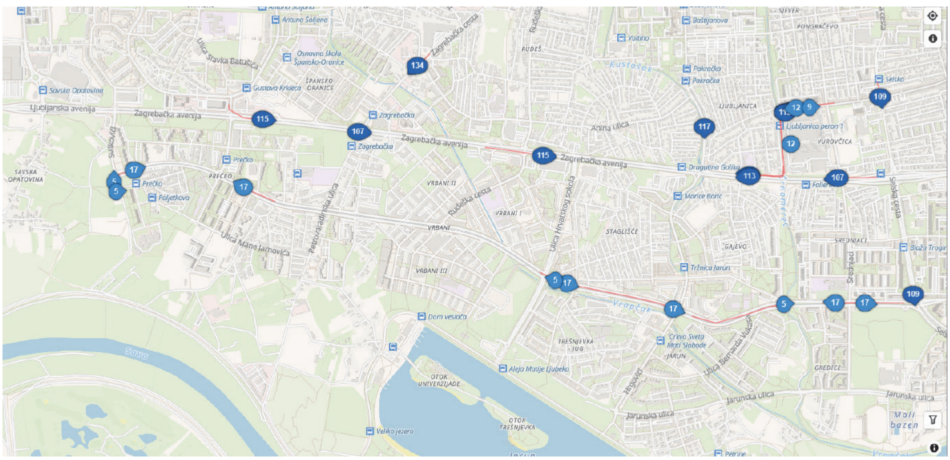

Figure 2 Display of the actual traffic situation from the “ZET shell” application [7]

This situation occurred because, due to previous bunching, multiple trams were dispatched from the Prečko terminus in quick succession in order to clear the tracks. As a result, two trams on line 17 were released into service with a headway that was approximately half of the required interval. Shortly afterwards, another tram on line 17 departed after a tram on line 5 for the same reason. The headway between the first and third trams on line 17 was slightly longer than optimal but still acceptable. Since an adequate headway existed between the first and third trams, in the second phase of this scenario the second tram on line 17 was redirected to the Savski most terminal. In doing so, it effectively became a new temporary line between Prečko and Savski most, designated as line 100, as shown in the figure 3. This figure illustrates a key aspect of the described scenario, showing tram positions, which served as the criterion for redistributing trams between different lines within the framework of this method. After arriving at Savski most terminal, this vehicle could be reassigned to operate on various lines departing from or passing near the terminal, such as lines 7, 14, 5, 17, or 4, depending on operational needs for maintaining balanced headways. This method can mitigate the negative effects of tram bunching in two ways. In the first one, by separating a tram number 17 that is already participating in the initial phase of bunching, the effect of additional accumulation of trams is prevented, because by continuing its journey, that tram would not have a significant benefit for passenger transport, since there are trams of the same line traveling in front of and behind it at a short distance, and possibly would only make it more difficult for other trams on the same or other lines that run parallel to it for part of the journey. In second way, this tram, with its redistribution to another line that passes through the nearby terminal to which the tram is sent, can reduce the excessive headway on that line and thus prevent a negative effect on the waiting time of passengers, as well as the occurrence of bunching behind the tram of that line, which is significantly behind the previous, initial tram. Within this scenario, the tram assigned to the new Line 100 is taken from Line 17 arrived at the Savski most terminal to replace a tram from line 7, which had departed 14 minutes earlier toward the city center as line 4 in order to reduce the excessively long headway on that line. In this way, the headway on line 4 was balanced, while the vehicle removed from line 7 which has a planned waiting in terminal was replaced by the vehicle from line 100 which than starts on time fro terminal as a tram on line 7. In this way, the redirected tram from Line 100 was used to reinforce service on Line 7 in order to maintain an optimal headway between vehicles operating on that tram line. In the final phase of the simulation scenario, the delayed tram from Line 7, after arriving at the Savski most terminal, was reassigned to Line 5, where an excessively long headway had occurred in the direction of the Prečko terminus; accordingly, it was on that line that an additional vehicle was most needed under the current traffic conditions.

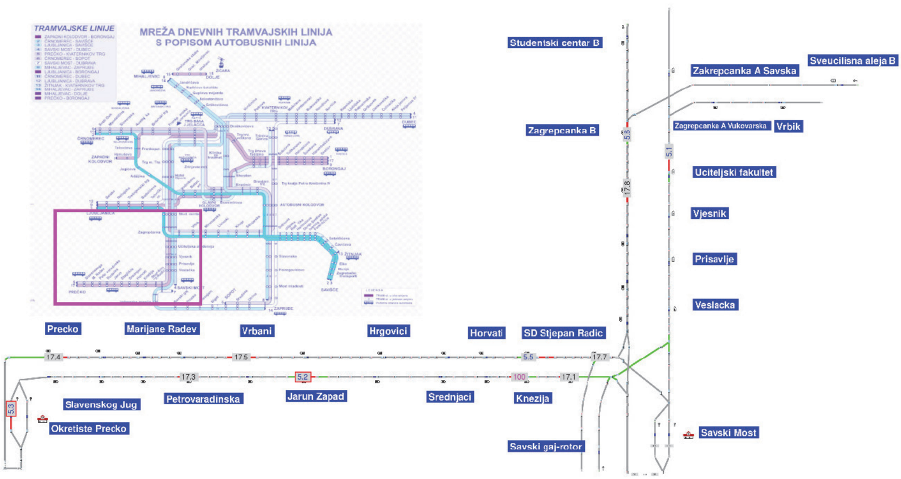

Figure 3 Output from the computer model shown in the OpenTrack software interface

In the second scenario, an example how this method can be used for the redistribution of tram vehicles along the same tramway line is simulated. In this scenario a tram of line 17 which is arriving from the Studentski centar stop was redirected to the Savski most terminal instead of continuing to its final stop at Prečko. From there, it was dispatched at the most favorable moment for maintaining headway on line 17 in the direction from which it had arrived. In this way, the vehicle remained in service on the same line (line 17), but its route was shortened. Instead of travelling all the way to the Prečko terminus, it changed direction at the Savski most terminal and returned toward the city center. This intervention effectively reduced an excessively long headway of 16 minutes on line 17 in the direction toward the city center.

4 Conclusion

As part of this research, a computer model of the observed section of the tram network in the city of Zagreb was developed, enabling the simulation of various scenarios of tram system behavior. By applying two different simulation scenarios on this model, the impact of a vehicle reallocation method on the optimization of headways between vehicles on the same and on different tram lines was evaluated. The simulation results indicate that the application of a vehicle redistribution method, combined with the introduction of a temporary tram service through timetable modification and the subsequent reassignment of vehicles between tram lines, can mitigate the negative effects of tram bunching in two ways. First, by separating a tram on Line 17 that is already involved in the initial phase of bunching, its potential negative impact on nearby trams is reduced, thereby preventing further accumulation of vehicles. Second, the separated tram can be used to reduce excessive headways on other tram lines, thus minimizing passenger waiting times and preventing the formation of additional bunching behind vehicles with large headway gaps ahead. By optimizing headways between trams in this way, passenger waiting times at stops can be significantly reduced, improving the overall quality of service and potentially encouraging more frequent use of public transport instead of private cars.
Future research will focus on the automated redistribution of vehicles between lines combined with automated tram control systems aimed at maintaining optimal headways under varying traffic conditions. Such an approach could further reduce the impact of unforeseen traffic situations on headway maintenance and the formation of tram bunching, thereby preserving the overall quality of tram transport services in terms of passenger waiting times.

References

[1] Newell, G.F., Potts, R.B.: Maintaining a fixed schedule by a single track line, University of Adelaide, 1964.

[2] Daganzo, C.F.: A headway-based approach to eliminate bus bunching: Real-time control and an indicator, with or without experiments, Transportation Research Part B: Methodological, 43 (2009) 10, pp. 913–924

[3] Yang, M., Ding, J., Wang, W., Ma, Y.Y.: A coordinated signal priority strategy for modern trams on arterial streets by predicting the tram dwell time, KSCE Journal of Civil Engineering, 22 (2018) 2, pp. 823–836

[4] Gardner, S., Casello, J., Bachmann, C.: Improving tram operations through transit signal priority: A comparative analysis, Journal of Public Transportation, 21 (2018) 2, pp. 64–82

[5] Šipuš, D., Lulić, T.: Analiza unaprjeđenja usluge prijevoza na tramvajskoj mreži Grada Zagreba primjenom prioriteta na raskrižjima, Promet - Traffic & Transportation, 29 (2017) 5, pp. 533–542

[6] Zagrebački električni tramvaj d.o.o.: Mreža tramvajskih linija, https://www.zet.hr/tramvajski-prijevoz/dnevne-linije/249, 09.03.2026.

[7] Zagrebački električni tramvaj d.o.o. (ZET): Eksploatacijski pokazatelji – svibanj 2025, https://zet.skoljka.org/, 02.2026.