



GNSS-BASED TRAM SPEED PROFILE MODELLING: A CASE STUDY OF THE ZAGREB TRAM NETWORK

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Abstract

Tram operating speed is a key indicator of public transport performance, directly affecting travel time, timetable reliability and overall service attractiveness. In urban environments, tram speed is highly variable due to infrastructure layout and traffic interference. This paper presents a methodological framework for modelling tram speed profiles based on extensive GNSS measurements collected under real-world operating conditions on the Zagreb tram network. The analysis is based on more than 93 hours of GNSS data, comprising over 340,000 position and speed records from regular tram operations. Maximum speeds were analysed between consecutive stopping events and modelled as a function of inter-stop distance and track position within the transport corridor. Separate logarithmic regression models were developed for segregated tram corridors, dedicated tracks within road corridors, and tracks operating within mixed traffic. Tram acceleration and deceleration behaviour was modelled using multi-stage linear models derived from empirically observed speed changes. The results confirm that tram speed cannot be represented by a single average value but must be described as a spatially dependent function influenced by infrastructure characteristics and operating conditions. The integrated speed profile model shows good agreement with measured data and provides a conservative representation of real-world tram operation. The proposed approach offers a robust analytical basis for timetable planning, performance evaluation and infrastructure-related analyses of tram systems.

Keywords: tram, speed profile, model, GNSS

1 Introduction

The operating speed of public urban transport vehicles is one of the key indicators of transport system efficiency, as it directly affects travel time, timetable reliability, and the overall attractiveness of the service to users [1]. In urban environments, where road space is limited and subject to multiple and often competing demands, achieving and maintaining adequate operating speeds for public transport represents a persistent challenge for transport planning and traffic management. Tram systems occupy a distinctive position within the urban transport systems of many European cities. As a form of guided transport, trams offer advantages in terms of capacity and energy efficiency; however, they are also highly sensitive to surrounding conditions. Unlike metro or railway systems, trams typically operate at street level and frequently interact directly with other traffic participants. As a result, tram operating speeds exhibit pronounced spatial and temporal variability [2]. In the city of Zagreb, the tram network forms the backbone of public passenger transport, extending through the historic city centre, densely built residential areas, and peripheral urban zones. A defining characteristic of the Zagreb tram system is the heterogeneity of track alignment within the transport corridor.

Tram tracks are partly located in fully segregated corridors, partly on segregated tracks within a roadway corridor and partly share the carriageway with road traffic. Each of these configurations exerts a distinct influence on tram operating speed and timetable stability [3].

Traditional approaches to tram speed analysis are commonly based on planned or normative values derived from design documentation, technical standards, or timetable assumptions. While such values are useful in the planning phase, they rarely capture the actual behaviour of vehicles under real traffic conditions. Observed tram speeds result from a complex interaction of factors, including driver behaviour, vehicle and track characteristics, and prevailing traffic conditions [4]. Vehicle speed can be measured using various methods. Conventional approaches, such as tachographs or onboard speedometers, provide direct information on instantaneous speed but lack precise spatial referencing, which limits their usefulness for analysing speed as a function of position along the network. In contrast, measurements based on Global Navigation Satellite Systems (GNSS) enable simultaneous tracking of both speed and position, allowing speed to be analysed as a spatial variable rather than solely as a function of time. Moreover, GNSS-based measurements facilitate the continuous collection of large datasets with high temporal resolution, enabling detailed analysis of the micro-dynamics of tram motion [5]. Despite these advantages, GNSS measurements in urban environments are subject to certain limitations, including reduced accuracy in densely built-up areas, signal multipath effects, and temporary signal loss [6]. Nevertheless, the availability of many repeated measurements along the same track sections allows statistical averaging, which supports the reliable identification of characteristic speed patterns.

Previous research on tram operating speed has often focused on average speeds at the line or section level, frequently neglecting acceleration and deceleration dynamics and the influence of stop spacing. However, acceleration and braking phases are critical for understanding system energy demand, vehicle and infrastructure wear, and for accurately modelling speed profiles. Consequently, over the past decade, increasing emphasis has been placed on empirical measurements of tram speed under real operating conditions. Against this background, the objective of this study is to develop an integrated tram speed profile model for the Zagreb tram network, based on an extensive GNSS dataset collected under real traffic conditions. Emphasis is placed on: (1) modelling typical acceleration and deceleration patterns, (2) determining maximum achievable speeds between consecutive stopping events, and (3) integrating these components into a unified speed profile along the track alignment. This approach provides deeper insight into the actual operational behaviour of the tram system and establishes a robust analytical basis for further traffic-engineering and infrastructure-related analyses.

2 Materials and methods

2.1 Data collection

The investigation of tram operating speeds was based on measurements of tram vehicle position and speed obtained using a GNSS receiver during regular urban public transport operations, collected through continuous multi-day measurements using the Sensornet SAM Infra monitoring system. This system was originally developed for continuous monitoring of the condition and quality of tramway system components, including track, overhead contact line, and rolling stock. However, its configuration, employing strategically positioned sensors mounted on the tram, also enables reliable acquisition of vehicle position data and fundamental dynamic characteristics, including operating speed [7]. Measurements were conducted over multiple days, including both weekdays and weekends, capturing a wide range of traffic conditions. Tram track sections located in different types of traffic corridors were analysed, including exclusive tram corridors, on-street (roadway) corridors, and segregated tram tracks.

This approach enabled an assessment of speed variability under different spatial configurations of the transport corridor. Furthermore, the analysed routes covered both central and peripheral urban areas, ensuring substantial spatial heterogeneity of traffic conditions. In total, 101 tram departures were recorded, yielding more than 340,000 individual position records and a cumulative operating time exceeding 93 hours. Time, position, and speed data were recorded with a temporal resolution of 1 s (sampling frequency of 1 Hz). The collected data were initially stored in the manufacturer's database and subsequently exported in a structured format for further processing and analysis.

Original GNSS records were referenced in the WGS84 geographic coordinate system. To enable integration with the planimetric geometry of the tramway track, the data were transformed into the official Croatian coordinate reference system HTRS96/TM. Following the transformation, each GNSS record was matched to the nearest tramway track centreline and assigned a corresponding chainage value. This procedure enabled the analysis of tram speed as a function of spatial position along the route, independent of the time of individual runs (figure 1).

2.2 Identification and modelling of maximum speed

Maximum speed was defined as the highest speed achieved by a tram along a track section between two consecutive stopping events, regardless of the cause of stopping. The analysis of maximum speed was conducted at the level of individual runs between consecutive stops, with each run treated as an independent unit of analysis. For each identified run, the travelled distance and the maximum achieved speed were determined, together with the position of the tram track within the traffic corridor. A total of 3,684 runs were identified, including 1,175 runs along tracks located within roadway corridors, 2,030 runs along tracks in exclusive tram corridors, and 479 runs along segregated tram tracks within roadway corridors.

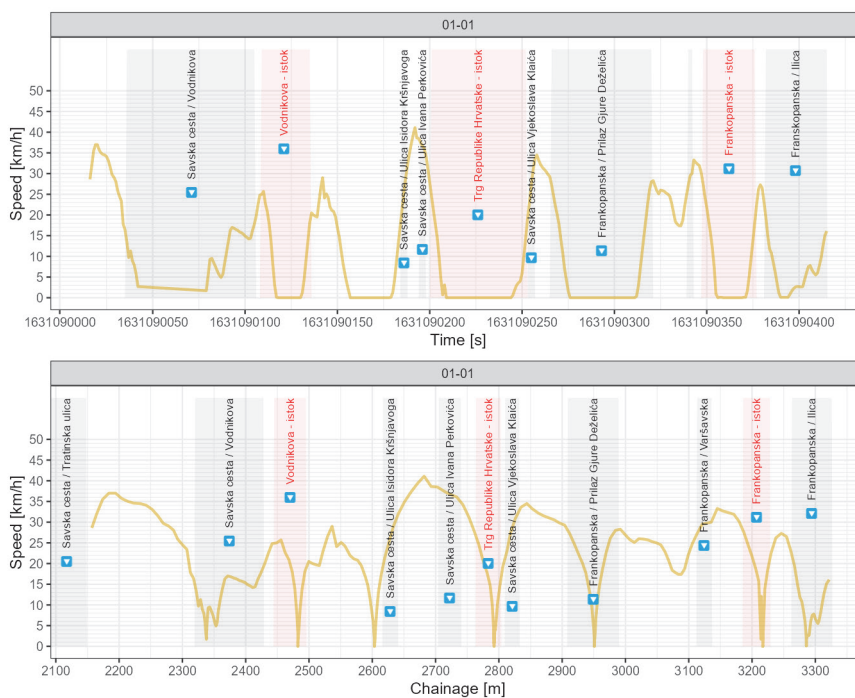


Figure 1 Speed variation as a function of time (upper panel) and travelled distance (lower panel)

Based on these runs, maximum speed estimation models were developed separately for each corridor type, considering the distance travelled between consecutive stopping events. The relationship between maximum speed and section length (figure 2) was modelled using logarithmic regression for each corridor configuration.

- For tracks in an exclusive tram corridor:

$$v_{\max} = 10.83 \log(L) - 19.44 \quad (1)$$

- For tracks in a roadway corridor:

$$v_{\max} = 7.28 \log(L) - 7.53 \quad (2)$$

- For segregated tracks within a roadway corridor:

$$v_{\max} = 8.51 \log(L) - 10.70 \quad (3)$$

where v_{\max} is the maximum speed achieved on the analysed section [km/h], and L is the distance between two consecutive stopping events [m].

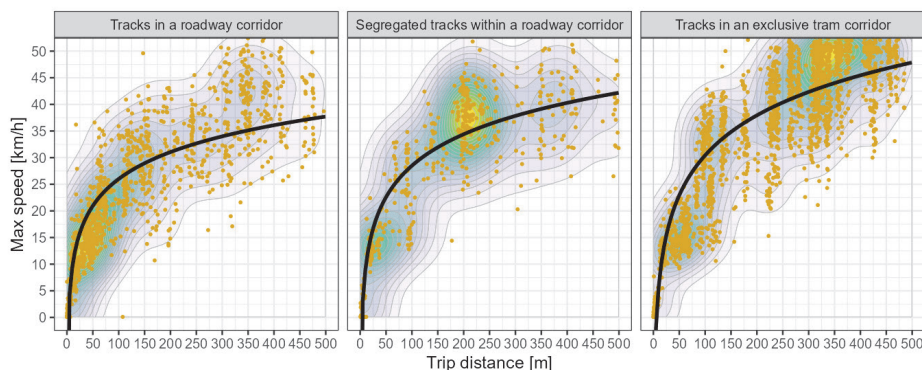


Figure 2 Distribution of max speed according to travelled distance

Model performance was evaluated using standard statistical indicators, including mean absolute error (MAE), mean absolute percentage error (MAPE), root mean square error (RMSE), and the coefficient of determination (R^2). The highest explanatory power was achieved for sections in exclusive tram corridors ($R^2 = 0.738$; MAE = 4.4 km/h; MAPE = 15.3%; RMSE = 5.5 km/h). Moderate accuracy was observed for segregated tracks within roadway corridors ($R^2 = 0.638$; MAE = 3.4 km/h; MAPE = 13.5%; RMSE = 4.3 km/h), while the lowest accuracy occurred on on-street sections within roadway corridors ($R^2 = 0.536$; MAE = 4.6 km/h; MAPE = 18.0%; RMSE = 5.7 km/h), reflecting increased traffic interference and variability of operating conditions.

2.3 Identification and modelling of acceleration and deceleration

Changes in tram speed – occurring during departures from and arrivals at stops, as well as due to speed limit changes or varying traffic conditions – were represented by acceleration and deceleration events. These events were identified by analysing speed differences between consecutive GNSS records. A total of 3,611 acceleration events and 3,471 deceleration events were identified. Each event was classified according to its initial and final speed, using speed classes with 5 km/h intervals over the range 0–50 km/h. Each class comprised more than 300 observations, ensuring statistical representativeness and enabling reliable inference of typical tram dynamic behaviour under different operating conditions.

To describe speed change dynamics, a multi-stage linear acceleration/deceleration model was adopted. The model consists of three consecutive phases: (1) gradual increase of acceleration up to a maximum value, (2) constant acceleration, and (3) gradual reduction of acceleration until the target speed is reached. This modelling approach provides a sufficiently accurate approximation of real tram dynamics while maintaining computational simplicity and numerical stability, making it suitable for speed profile modelling [8]. The acceleration model is defined as:

$$a(t) = \frac{a_m}{t_1} \cdot t \text{ for } t \in [t_0, t_1] \quad (4)$$

$$a(t) = a_m \text{ for } t \in [t_1, t_2] \quad (5)$$

$$a(t) = a_m + \frac{a_m}{t_3 - t_2} (t - t_2) \text{ or } t \in [t_2, t_3] \quad (6)$$

where a_m is the maximum acceleration [m/s²], and $t_0 - t_3$ denote phase transition times [s]. The deceleration model follows an analogous formulation with reversed time intervals and negative acceleration values:

$$a(t) = a_m + \frac{a_m}{t_3 - t_2} (t - t_2) \text{ for } t \in [t_3, t_2] \quad (7)$$

$$a(t) = a_m \text{ for } t \in [t_2, t_1] \quad (8)$$

$$a(t) = \frac{a_m}{t_1} \cdot t \text{ for } t \in [t_1, t_0] \quad (9)$$

Model parameters were derived statistically for each speed class (table 1).

Table 1 The acceleration/deceleration model parameters

Speed difference [km/h]	Acceleration					Deceleration				
	+10	+20	+30	+40	+50	-10	-20	-30	-40	-50
a_m [m/s ²]	0.90	1.10	1.20	1.20	1.30	-0.70	-1.15	-1.20	-1.30	-1.45
t_1 [s]	2.5	2.8	2.5	3.0	3.5	-1.5	-2.5	-2.5	-2.8	-2.7
t_2 [s]	3.5	3.9	4.5	7.5	6.9	-2.4	-3.2	-3.4	-4.9	-5.8
t_3 [s]	5.0	9.0	12.0	14.0	18.0	-7.0	-9.0	-13.0	-15.0	-16.0

Model accuracy was assessed by comparing modelled and measured speed and distance values (figure 3) using MAE, RMSE, and R². Mean absolute speed errors ranged from 0.3 to 0.9 km/h with RMSE values between 0.3 and 1.0 km/h. For travelled distance, MAE ranged from 2.0 to 8.6 m and RMSE from 2.3 to 10.2 m. Coefficients of determination indicated strong correlations (R₂ > 0.98) between measured and modelled values for all analysed cases.

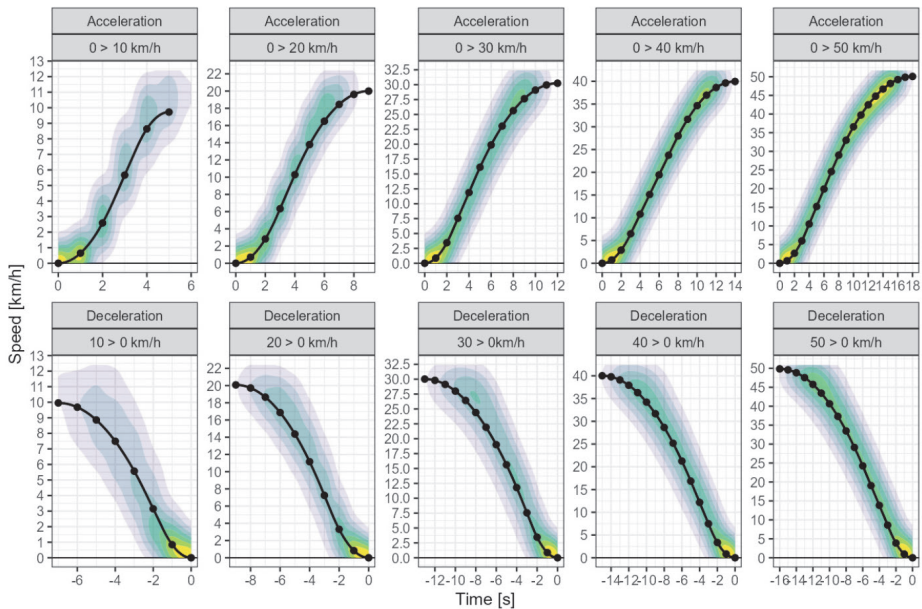


Figure 3 Acceleration/deceleration speed change dynamics

2.4 Tram speed profile modelling

The tram speed profile (figure 4) represents the dynamic behaviour of the vehicle along the track and enables the identification of key spatial and operational elements influencing system efficiency, punctuality, and service quality. The speed profile along the tramway was modelled through the integration of three components: maximum speed profile, acceleration profile, and deceleration profile. The maximum speed profile was defined using the developed empirical maximum speed models, based on the distance between consecutive stopping events and the position of the track within the traffic corridor. Both regulatory speed limits [9, 10] – a maximum tram speed of 50 km/h – and local speed restrictions imposed for safety and infrastructure protection were considered.

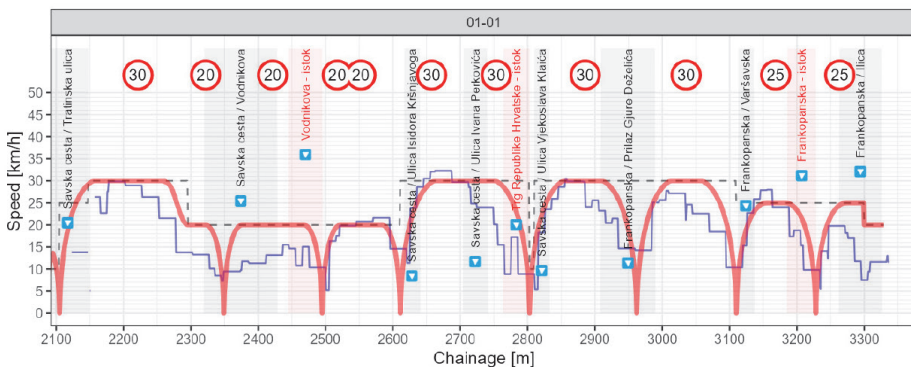


Figure 4 Modelled speed profile

Acceleration and deceleration profiles were generated using the developed multi-stage models, accounting for the spatial distribution of stopping events and the corresponding initial and final speeds. Tram stops were included as mandatory stopping locations. In addition, analysis of empirical speed profiles showed that, due to the absence of systematic public transport signal priority, signalised intersections represent significant potential forced stopping points and were therefore incorporated into the model.

Model accuracy was evaluated by comparing modelled and measured mean speeds aggregated over consecutive 10 m analytical track segments, providing sufficient spatial resolution to capture relevant patterns while reducing the influence of short-term speed fluctuations. Mean absolute errors of average speed ranged from 6.2 to 6.9 km/h, with mean absolute percentage errors between 24.2% and 29.0%. RMSE values ranged from 7.8 to 8.7 km/h, depending on corridor type. Observed deviations were predominantly positive, indicating a systematic tendency of the model to slightly overestimate tram operating speeds relative to empirical observations.

3 Results and discussion

The analysis of empirical GNSS data clearly confirms that the maximum achievable speed of a tram vehicle increases with the length of travel between two consecutive stopping events, regardless of the cause of stopping. In other words, longer inter-stop distances allow for an extended acceleration phase and a longer period of constant-speed operation, resulting in higher values of maximum attained speed. This finding is consistent with theoretical expectations and previous studies on the dynamics of public transport vehicles. At the same time, the results indicate that the position of the tram track within the transport corridor has a significant influence on achievable speeds. Sections where the track is in a segregated tram corridor or in a dedicated track within the road corridor exhibit a higher likelihood of reaching the maximum permitted speeds compared with sections located entirely within the road corridor, where the tram shares the space with other road users. Increased traffic interference, frequent signalised intersections, and greater variability in traffic conditions on such sections substantially limit the possibility of achieving higher speeds. A more detailed analysis reveals pronounced differences in typical travel distances and corresponding maximum speeds depending on the spatial position of the track. On sections within the road corridor, trams most commonly travel distances of up to approximately 120 m, reaching maximum speeds of around 25 km/h. On segregated tracks, typical travel distances range from approximately 270 to 425 m, with maximum speeds between 40 and 50 km/h. Sections with tracks in a dedicated alignment within the road corridor represent an intermediate case, with typical travel distances of 150 to 250 m and maximum speeds in the range of 30 to 45 km/h. These results further confirm the strong relationship between the spatial position of the track within the transport corridor and the dynamic characteristics of tram movement. Accordingly, physical segregation of tram traffic from general road traffic plays a crucial role in ensuring higher and more stable operating speeds, directly affecting timetable reliability and the overall efficiency of the system.

4 Conclusion

GNSS-based monitoring, as a tool for improving efficiency, reliability, and sustainability in tram system management, has a wide range of potential operational applications. For example, such data enable real-time monitoring of service regularity and operational disturbances, as well as timetable planning by providing realistic speed distributions under actual traffic conditions. Furthermore, they offer opportunities for analysing and optimising energy consumption and for supporting driver training through objective performance evaluation.

This study developed a methodological framework for modelling tram speed profiles based on GNSS measurements under real traffic conditions. The results demonstrate that tram speed cannot be represented by a single value, but rather as a function of spatial location, infrastructural constraints, and the surrounding traffic environment. A key contribution of this work is the integration of acceleration, deceleration, and maximum speed models into a unified speed profile, enabling the assessment of the spatial distribution of speeds across the entire network. This approach has broad applicability in timetable planning, evaluation of public transport efficiency, and analysis of speed impacts on track wear and degradation. Future research could include more detailed segmentation by time of day, weather conditions, and vehicle type, as well as integration of the model with traffic signal control systems.

Acknowledgments

The authors would like to thank Zagreb Electric Tram Ltd. for their support and for providing data from the Study on the Development of Tram Transport in the City of Zagreb.

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