Comparative analysis of accelerometric measurement results of trams with 1000 mm and 1435 mm track gauge

Analiza porównawcza wyników pomiarów akcelerometrycznych dla tramwajów o rozstawie 1000 i 1435 mm



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Abstract: The article presents a comparative analysis of dynamic interactions in standard-gauge (1435 mm) and narrow-gauge (1000 mm) tram systems, based on accelerometric measurements conducted in Olsztyn and Toruń. The study aimed to determine the impact of track parameters and rolling stock characteristics on vibration levels affecting passenger comfort and safety. Measurements carried out under normal operating conditions for Solaris Tramino, Durmazlar Panorama, Pesa Swing, and Konstal 805NaND vehicles allowed for the identification of significant differences in the dynamic response of specific designs to track surface irregularities. It was demonstrated that the Durmazlar Panorama model and the older Konstal-type rolling stock are susceptible to generating high lateral accelerations in areas of degraded infrastructure, reaching values that compromise passenger stability, whereas vehicles such as the Solaris Tramino exhibit significantly better damping properties. The obtained results demonstrate that track geometry and suspension type have a dominant influence on the dynamics of the track-vehicle system, providing a basis for further analysis of ride comfort indices according to the PN-EN 12299 standard.

Keywords: *Accelerometric Measurements; Dynamic Interaction; Transport; Tram; Track Gauge*

Streszczenie: Niniejszy artykuł przedstawia analizę porównawczą oddziaływań dynamicznych w systemach tramwajowych o rozstawie normalnym (1435 mm) i wąskim (1000 mm), opartą na badaniach akcelerometrycznych przeprowadzonych w Olsztynie i Toruniu. Celem pracy było określenie wpływu parametrów toru oraz charakterystyki taboru na poziom drgań wpływających na komfort i bezpieczeństwo podróży. Pomiary zrealizowane w warunkach normalnej eksploatacji dla pojazdów Solaris Tramino, Durmazlar Panorama, Pesa Swing oraz Konstal 805NaND pozwoliły na identyfikację istotnych różnic w odpowiedzi dynamicznej poszczególnych konstrukcji na nierówności nawierzchni. Wykazano, że model Durmazlar Panorama oraz starszy tabor typu Konstal są podatne na generowanie wysokich przyspieszeń poprzecznych w miejscach degradacji infrastruktury, osiągających wartości zagrażające stabilności pasażerów, podczas gdy pojazdy takie jak Solaris Tramino wykazują znacznie lepsze właściwości tłumiące. Uzyskane wyniki dowodzą, że geometria toru i typ zawieszenia mają dominujący wpływ na dynamikę układu tor-pojazd, stanowiąc podstawę do dalszych analiz wskaźników komfortu według normy PN-EN 12299.

Słowa kluczowe: *Pomiary Akcelerometryczne; Transport; Tramwaj; Szerokość Toru*

Introduction

Accelerometric measurement in rail transport is crucial for an accurate assessment of passenger ride quality. Vibration analysis allows for an understanding of how the track structure and geometry influence travel comfort. The technical condition of the rolling stock, including damping systems and vehicle-generated vibrations, can also significantly affect the dynamic loads experienced by passengers. These measurements enable the optimization of both infrastructure and rolling stock, which, in the long term, enhances the comfort and safety of transport users.

This paper presents a comparative analysis of measurement results obtained from trams with track gauges of 1000 mm and 1435 mm, recorded under real operating conditions. Particular attention is paid to the relationships between track structure, vehicle type, and the values of recorded accelerations, which is essential for assessing

infrastructure condition and public transport quality. The study and analysis aimed to examine the differences in dynamic impacts occurring as a result of the specific tram track gauge used. The objective was to evaluate how variations in track design affect vibration levels recorded inside the vehicle and, consequently, passenger ride comfort.

The scope of the research included the selection of representative test sections, preliminary processing and filtering of accelerometric data, the generation of acceleration profile graphs, and the analysis and interpretation of the results. This was done to determine the impact of track gauge, pavement structure, and rolling stock type on the level of dynamic interactions within the vehicle.

Accelerometric Measurements in Rail Transport

Accelerometric measurements have become a key tool in diagnosing the technical condition of rail infrastructure and assessing ride comfort in rail vehicles, including trams, since the early 1990s. This period marked a time when the development of measurement technologies and increasing demands for passenger comfort began to influence diagnostic standards in rail transport. The growing importance of this type of research is reflected both in technical standards and in national and international scientific publications. According to the PN-EN 12299:2009 standard, acceleration measurements form the basis for determining passenger ride comfort indices across three axes, taking into account the influence of vibration frequency and amplitude [23]. This standard is supplemented by international guidelines such as ISO 2631-1 [17] and UIC 518 [34], which define permissible vibration levels and evaluation principles.

The literature on the subject places particular emphasis on the significance of track quality and track geometry in generating vibrations. The works of Piotrowski [22] and Scholz [29] indicate that the condition of the track surface, the type of structure used (e.g., classic, vibration-isolated, or ballastless tracks), and the presence of geometric defects have a direct impact on the level of vibrations perceived within the vehicle. Furthermore, the importance of accelerometers as measurement tools for both comfort assessment and the detection of track and tram wheel damage is highlighted. On the other hand, the publication by Majali [14] analyzes the frequency distribution of the accelerometric signal depending on the subgrade condition and weather conditions, pointing to the significant impact of moisture and temperature on vibration propagation.

Among international studies, the work of Bocz et al. [4] is noteworthy, where time-frequency analysis (wavelet transform) was used to identify vertical defects in tram tracks. The application of triaxial MEMS accelerometers enabled the automatic detection and high-precision localization of track discontinuities [5]. Similarly, Zhang et al. [43] utilized fiber-optic accelerometers for long-term vibration monitoring of concrete tracks, analyzing the effect of temperature changes on the dynamic response of the track.

In the context of comparing different track gauges (1000 mm and 1435 mm), research indicating differences in the dynamic reactions of vehicles to track irregularities is of great importance. These variations stem not only from the different geometries of vehicles and tracks but also from differences in curve radii, structural stiffness, and pavement types. Works such as *Modernization of Heavy Loaded Tram* [21] or the analysis of the impact of the analytical track section length on data quality demonstrate how local segmentation and analysis of accelerometric data allow for a precise assessment of the impact of these parameters on ride comfort and safety [15]. Furthermore, Zhang et al. [44], as well as Sadeghi, Oregui, and Li [19], investigate the use of data from sensors placed on bogies and axle boxes for continuous track quality monitoring.

Aspects of modeling and processing accelerometric signals were discussed in the works of Kamenev [20], Galvín et al. [7], and Knothe and Grassie [37], who applied numerical methods and wavelet transforms to analyze dynamic phenomena at the wheel-rail interface. Concurrently, Kaewunruen and Remennikov, along with Berggren and Jonsson [3], analyzed track stiffness as a parameter significantly influencing vibration magnitude. It is also worth mentioning systems based on optical sensors, predictive technologies, and passenger load estimation using acceleration data. These are complemented by the classic studies of Esveld [6] and Grassie [10], which provide the foundation for understanding the mechanics of rail and wheel fatigue.

Research Methodology

The analysis was based on field studies conducted between 2023 and 2024 as part of the research project titled "*Accelerometric measurements in passenger rail vehicles*," aimed at assessing the impact of unbalanced accelerations on passenger comfort and subjective perceptions. A more extensive description of the research methodology can be found in [36].

Measurements were carried out under real operating conditions using mobile devices equipped with triaxial MEMS accelerometers and GPS modules, such as smartphones. Data registration was performed using the professional Physics Toolbox Sensor Suite Pro application, which allows for the simultaneous recording of acceleration, speed, and location. The equipment was mounted on stable surfaces inside the vehicles to minimize the influence of local vibrations and ensure the repeatability of measurements.

During the test runs, unbalanced accelerations were recorded across

three axes, along with vehicle speed, geographic coordinates, and subjective comfort ratings according to the NMV scale specified in the PN-EN 12299 standard [23]. The study encompassed both trams and railway passenger vehicles (EMUs and DMUs), allowing for a comparison of dynamic impacts across different types of rail transport. The collected data was used to analyze how track construction, rolling stock type, and traffic conditions affect the level of acceleration experienced by passengers.

Measurements were conducted in four cities with rail transport systems: Bydgoszcz, Toruń, Olsztyn, and Gdańsk, as well as on selected railway lines. The selection of research areas was intentional, resulting from the diversity of the analyzed transport systems. Differences in track gauge, infrastructure characteristics, and the functional role of tram lines within the urban layout were taken into account.

For detailed investigation, the tram networks in Olsztyn and Toruń were selected. In Olsztyn, the analysis covered three tram lines with a total length of approximately 21 km. In Toruń, the study was conducted on two tram lines with a total length of approximately 22.75 km. Four types of tram vehicles were utilized in the study: Solaris Tramino and Durmazlar Panorama operated in Olsztyn, as well as Pesa Swing 121NbT and modernized Konstal 805NaND cars running in Toruń.



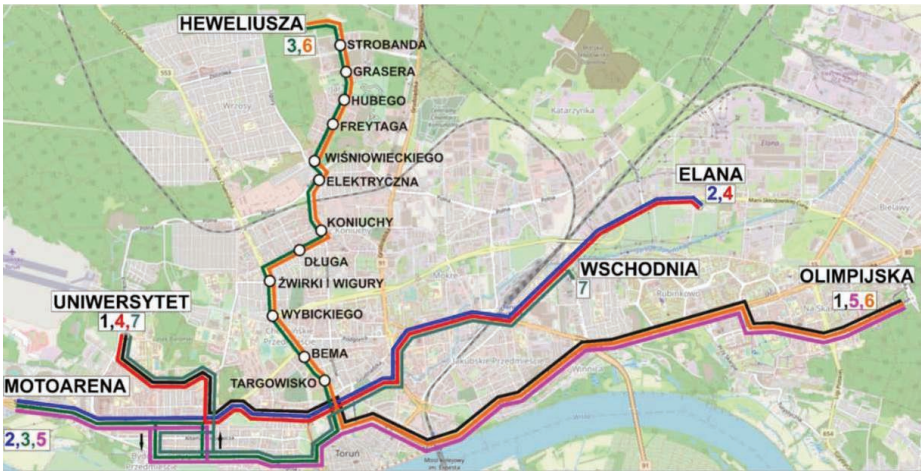
***1**. Diagram of tram lines in Olsztyn. Source: [8]*

Research Testbed

Tram network in Olsztyn

The selection of Olsztyn and Toruń (Poland) as research testbeds was preceded by an analysis of several technical and urban filters. The homogeneity and new condition of the track infrastructure were of key importance, allowing for the reduction of variability resulting from rail surface wear. Additionally, such a combination made it possible to include differences in track gauge (standard 1435 mm and narrow 1000 mm) while maintaining a comparable level of engineering advancement in the applied solutions. An important criterion was also the functional role of the tram lines in the urban layout and their integration with other modes of transport. This enabled the analysis of the influence of track parameters and network geometry on driving dynamics.

The research testbed included two tram networks: those of Olsztyn and Toruń. Their combination allows for the simultaneous analysis of the latest domestic track solutions and the verification of the impact of track gauge on the dynamic parameters of the track-vehicle system. In Olsztyn, the entire infrastructure was built in 2015 and was successively expanded until 2024. The tracks were made using precast slab technology with the use of curve lubricators. Three tram lines (1, 4, and 5) were selected for the study, connecting the city's most important functional areas residential estates, transport hubs, and the strict city cen-



***2**. Diagram of tram lines in Toruń . Source: [9]*



a) *b)* *c)* *d)*

***3**. Tram rolling stock used: a) Solaris Tramino S111O tram, b) Durmazlar Panorama, c) Pesa Swing tram, d) Konstal 805NaND. Source: [25-28]*

ter. The tram network is shown in Figure **1**.

Tram network in Toruń

The tram network in Toruń is characterized by a narrower track gauge and possesses comparably modern infrastructure, which was modernized in 2014. Tram lines 3 and 5 run through Toruń's dynamically developing districts including Jar, Bielawy, the University District, and the southern part of Wrzosy as well as through the densely built-up city center and attractive recreational areas by the Vistula River. They utilize ballastless track structures with vibration-damping elements and energy-efficient turnouts. Both analyzed sections serve 35 stops each. Line No. 3 in Toruń is 10.5 km long. The tram network in Toruń is shown in Figure **2**.

The similarity of both tram networks in terms of the maintenance condition of the infrastructure considering its relatively young age and the simultaneous diversification in track gauge and rolling stock type create favorable conditions for a comparative analysis of dynamic interactions affecting ride comfort, safety, and the technical condition of the track and vehicles.

Tram rolling stock used during the research

The presented networks are operated by the following vehicles: Solaris Tramino (Fig. **3a**), Durmazlar Panorama (Fig. **3b**) (in Olsztyn), and Pesa Swing 121NbT (Fig. 3c), as well as modernized Konstal 805NaND (Fig. **3d**) (in Toruń).

A comparison of the key technical parameters of the rolling stock operated in Olsztyn and Toruń includes, among others, vehicle length, number of sections, track gauge, and the power of the propulsion systems. The data presented in this manner allows for a direct comparison of the design of the trams used in both networks and an assessment of their potential impact on the dynamic characteristics of the track–vehicle system, as shown in Table **1**.

Data Analysis

Recorded Lateral and Vertical Accelerations during tram runs in Olsztyn

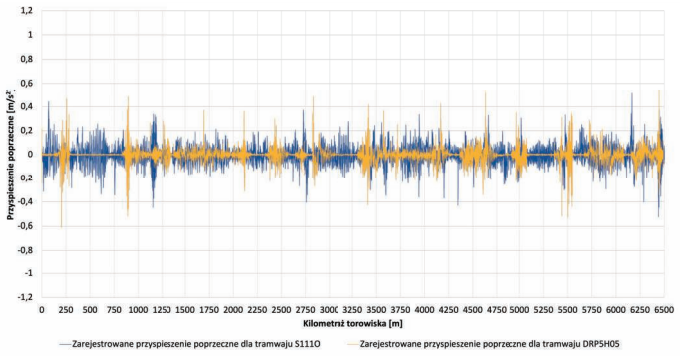
As part of the subsequent procedures, data filtration was performed, involving the isolation of measurements that were complete, undamaged, and conducted at a single measurement point on the same day. Subsequently, a comparison of the measurement results was carried out, taking into account differences resulting from the type of tram rolling stock and the track gauge. This analysis allowed for the determination of the impact of individual factors on the technical parameters of the track. The graphs presented below represent the average of the data collected during runs from measurement point No. 1 (located at the front of the vehicle). Approximately 16 measurement files were obtained from each run.

Three tram runs were utilized for the analysis, covering Line No. 4 (Dworzec Główny – Pieczewo) and Line No. 1 (Wysoka Brama – Kanta). Notably,

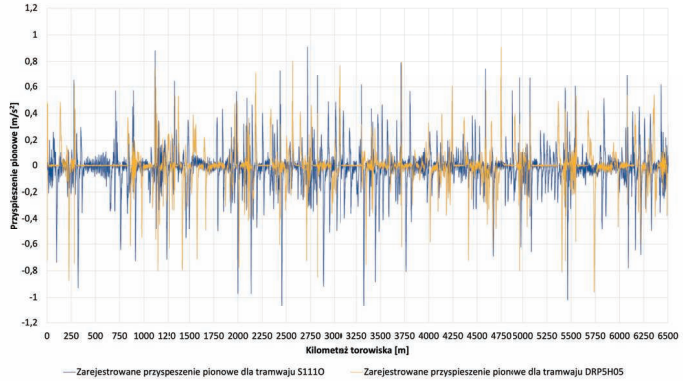
***Tab. 1.** Comparison of basic technical parameters of the rolling stock used*

Model	L. czł.	Len. [m]	Wid. [m]	Gauge [mm]	Vmax [km/h]	Motors[kW]	Curb/gross [t]	Seats/ stand.	Axle load [kN]
Panorama DRP5H05	5	32.5	2.50	1435	75	b.d.	b.d.	~40 / ~210	93.87
Solaris Tramino S1110	3	29.3	2.50	1435	75	4 x 120	43	43 / >230	99.9
Pesa Swing 122NbT	5	30.12	2.35	1000	70	4 x 105	41.6	~40 / —	b.d.
Konstal 805NaND	1	13.5	2.40	1000	70	4 x 41.5	b.d.	20 / 99	b.d.

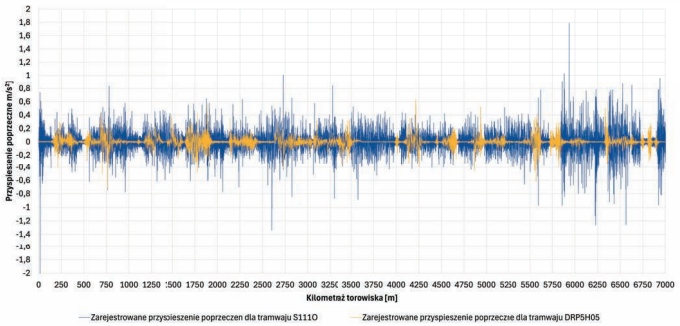
Source: own work based on [18,31,32]



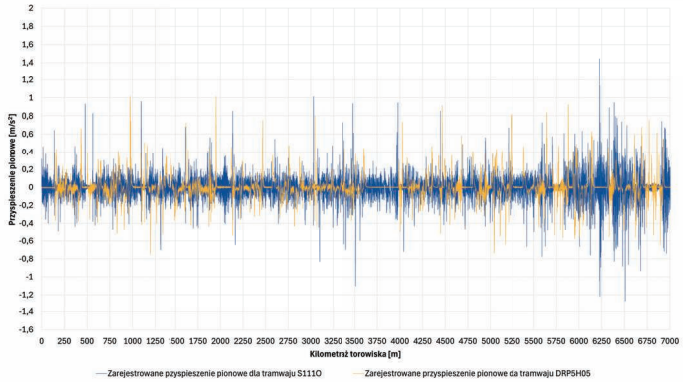
***4**. Lateral acceleration for Line No. 4 (Dworzec Główny – Pieczewo) for S111O and DRP5H05 rolling stock. Source: own work based on data [36]*



***5**. Vertical acceleration for Line No. 4 (Dworzec Główny – Pieczewo) for S111O and DRP5H05 rolling stock. Source: own work based on data [36]*



***6**. Lateral acceleration for Line No. 4 (Pieczewo – Dworzec Główny) for S111O and DRP5H05 rolling stock. Source: own work based on data [36]*



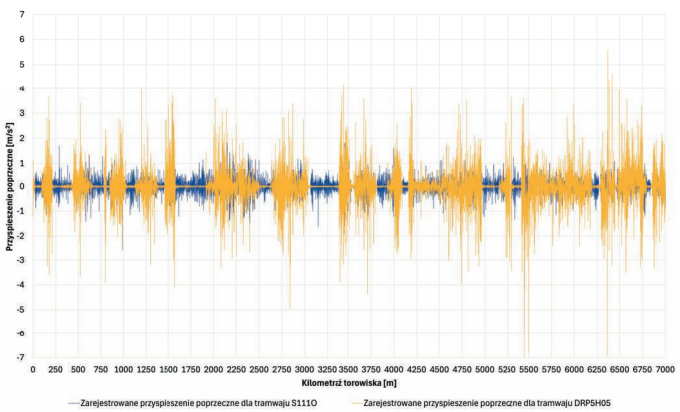
***7**. Vertical acceleration for Line No. 4 (Pieczewo – Gdańsk Główny) for S111O and DRP5H05 rolling stock. Source: own work based on data [36]*

measurements for two different tram models (DRP5H05 and S111O) in both directions were not conducted solely on Line No. 1.

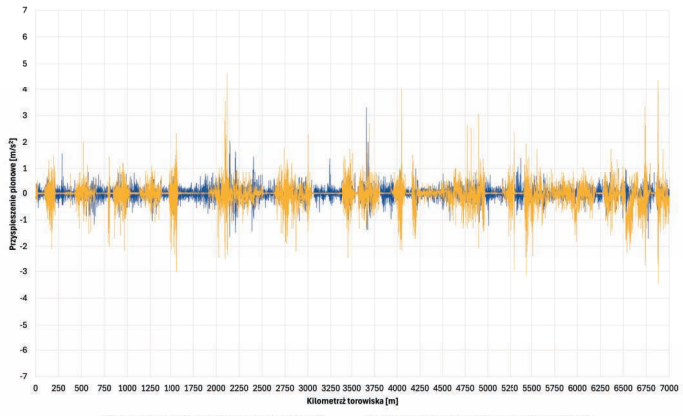
Figure *4* illustrates the lateral accelerations recorded for Line No. 4 on the Dworzec Główny – Pieczewo route. The values are significantly lower than those for vertical vibrations, with the majority falling within the range. Higher vibration density is evident on several sections of the route, which may result from track geometry or bogie hunting (oscillatory motion). It can also be observed that the DRP5H05 tram model exhibits a wider band of low-amplitude vibrations in many locations, whereas the S111O model shows more localized but abrupt spikes.

Figure **5** illustrates the vertical acceleration for Line No. 4 on the Dworzec Główny – Pieczewo route. Both trams exhibit numerous acceleration spikes exceeding, which may suggest vertical track irregularities. The S111O tram shows peaks that are approximately higher and more densely concentrated in certain track sections. This could indicate a stiffer primary suspension or a different mass distribution in this particular model.

Figure **6** presents the lateral accelerations for Line No. 4 on the Pieczewo – Dworzec Główny route. It can be observed that the S111O tram generates significantly larger acceleration peaks, particularly in the final stage of the route (from 5,750 m to 7,000 m), reaching as high as. This is a very high value, which may cause strong lateral jerks that are clearly perceptible, espe-



***8**. Lateral acceleration for Line No. 1 (Wysoka Brama – Kanta) for S111O and DRP5H05 rolling stock. Source: own work based on data [36]*



***9**. Vertical acceleration for Line No. 1 (Wysoka Brama – Kanta) for S111O and DRP5H05 rolling stock. Source: own work based on data [36]*

cially to standing passengers. In contrast, the DRP5H05 model is considerably more stable; its vibrations rarely exceed, suggesting significantly better damping of hunting oscillations.

Figure **7** presents the vertical acceleration for Line No. 4 on the Pieczewo – Dworzec Główny route. Both trams react at the same points (approx. 1,000 m, 2,000 m, 4,000 m, and 6,250 m), which suggests the existence of specific track defects, such as dipped rail joints. In both cases, the maximum values oscillate between 1.0 m/s^2 and 1.5 m/s^2. The S111Omodel tends to exhibit larger acceleration peaks, which is particularly visible at the 6,250-meter mark of the trackage.

Figure **8** presents the lateral acceleration for Line No. 1 on the Wysoka Brama – Kanta section. The DRP5H05 tram exhibits extreme peaks ranging from – 7 m/s^2 to 5.5 m/s2. These values significantly exceed comfort standards (values above are generally classified as high discomfort). In contrast, the S111O model performs much more stably, with its lateral accelerations rarely exceeding 1 m/s^2.

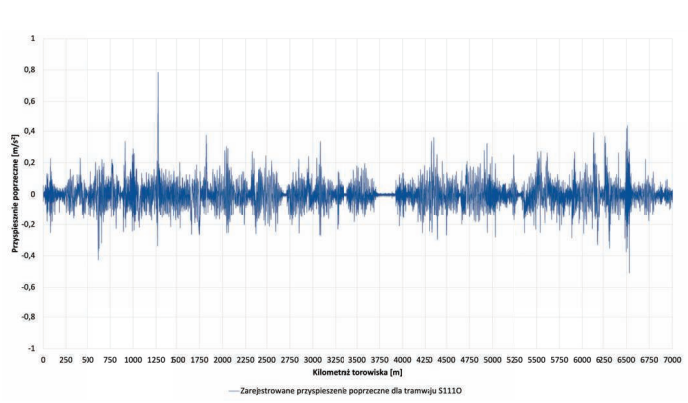
Figure **9** also shows significant peaks at similar locations along the track mileage as in the previous graph (Fig. 5), for instance, at approximately 2,100 m, 3,700 m, 5,500 m, and 6,800 m. This may be caused by defects in track geometry or an unstable positioning of the measuring device. It clearly points to track infrastructure flaws, such as worn-out turnouts or damaged rail joints. It is evident that the DRP5H05 tram generates higher vertical peaks (up to 4.5 m/s^2) compared to the S111O model (up to 2 m/s^2).

For the Kanta – Wysoka Brama direction, analogous areas of increased acceleration values are noticeable; however, their distribution is more localized, which may indicate local track irregularities (Figs. **10**,**11**). On the Kanta – Wysoka Brama section of Line No. 1, measurements were conducted exclusively using the S111O rolling stock.

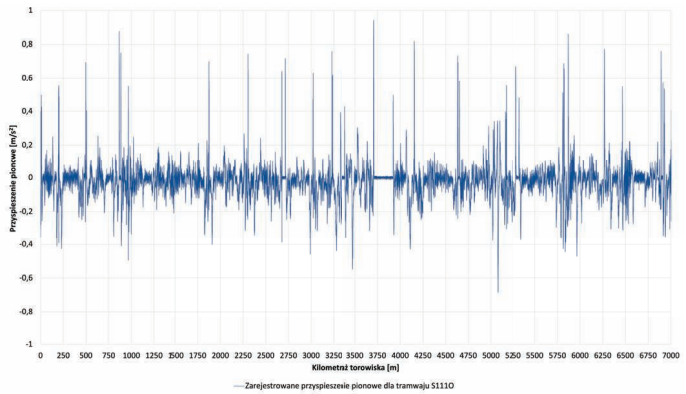
Recorded Lateral and Vertical Accelerations during Tram Runs in Toruń

The analysis was conducted based on four tram runs for lines No. 5 and No. 3. Measurements were performed in both directions for two different tram models (except for the route on line No. 3, Heweliusz – Motoarena). The graphs presented below represent the average data from the runs along the route from measurement point No. 1 (located at the front of the vehicle). Approximately 10 measurement files were obtained for each run.

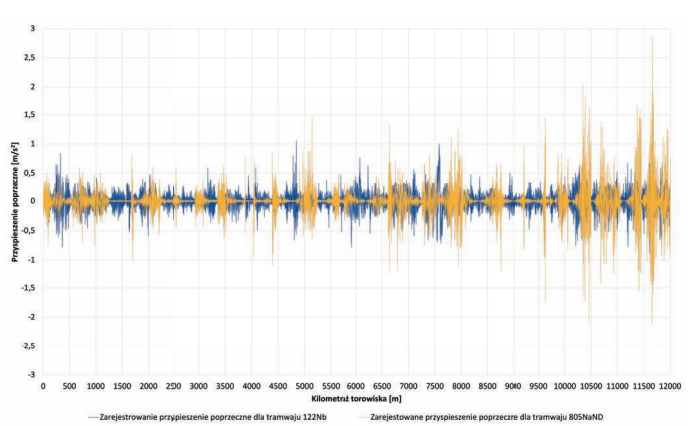
The first figure (Fig. **12**) illustrates the lateral acceleration for line No. 5 on the Motoarena – Olimpijska P&R route. As can be observed, for most of the route (up to approximately 9,000 m), both vehicles behave stably, with



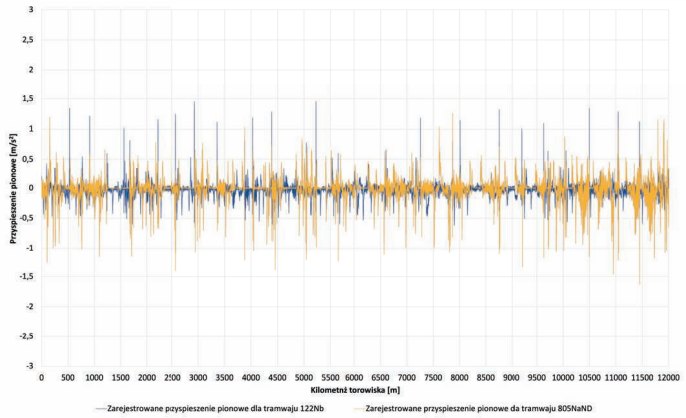
***10**. Lateral acceleration for Line No. 1 (Kanta – Wysoka Brama) for S111O rolling stock. Source: own work based on data [36]*



***11**. Vertical acceleration for Line No. 1 (Kanta – Wysoka Brama) for S111O rolling stock. Source: own work based on data [36]*



***12**. Vertical acceleration for Line No. 5 (Motoarena – Olimpijska P&R) for 122Nb and 805NaND rolling stock. Source: own work based on data [36]*



***13**. Lateral acceleration for Line No. 5 (Motoarena – Olimpijska P&R) for 122Nb and 805NaND rolling stock. Source: own work based on data [36]*

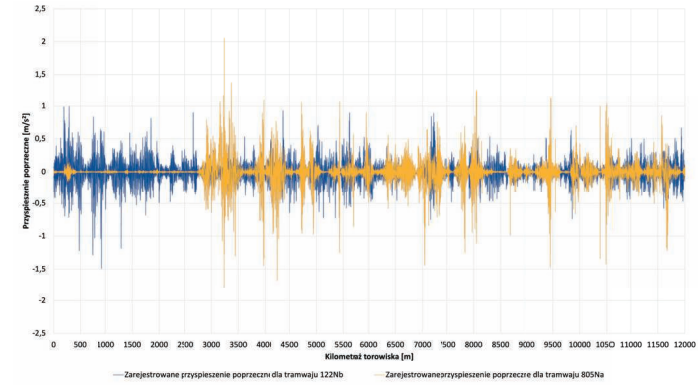
acceleration not exceeding 1.0 m/s^2. From 11,000 m until the end of the route, a sharp increase in lateral accelerations is visible. The 805NaND vehicle exhibits extreme peaks reaching nearly 3.0 m/s^2, while the 122Nb model remains within the range of approximately 2.0 m/s^2. The increase in vibrations on the final section suggests either an increase in travel speed on lower-quality trackage or the occurrence of lateral bogie resonance in the 805NaND model.

Figure **13** presents the vertical acceleration for Line No. 5 on the Motoarena – Olimpijska P&R route. The 122Nb vehicle exhibits higher but very localized acceleration peaks, reaching values of approximately 1.5 m/s^2. This suggests a stiffer primary suspension characteristic, which transmits shocks very precisely. In contrast, the 805NaND model generates a denser band of vibrations with a slightly lower amplitude (maximum 1.2 m/s^2), which may indicate better damping of high-frequency vibrations. Numerous recurring peaks in both signals (around 2,750 m, 4,250 m, and 6,750 m) confirm the presence of local infrastructure defects most likely worn rail joints.

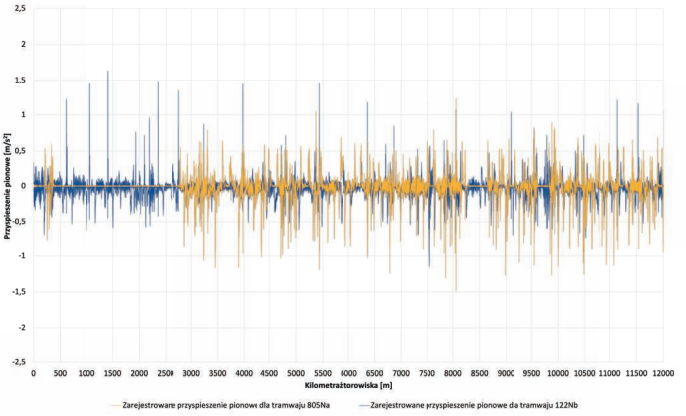
Figure *14* presents the lateral acceleration for Line No. 5 on the Olimpijska P&R – Motoarena route. It can be observed that the 122Nb vehicle exhibits very high stability during the first phase of the route up to approximately 3,000 m, where the vibration amplitude is minimal. Only on subsequent sections do the vibrations increase, though they do not exceed 1.0 m/s^2. The 805NaND tram generates significantly higher lateral acceleration, particularly visible around 3,500 m, where peaks reach 2.0 m/s^2. In the second half of the route, the vehicle shows a constant, high vibration amplitude, suggesting poorer bogie-track interaction.

Figure **15** presents the vertical acceleration for Line No. 5 on the Olimpijska P&R – Motoarena route. Similar to the lateral plane, the 122Nb vehicle is highly stable at the beginning of the route, whereas the 805NaND model generates a denser band of higher-frequency vibrations from the very start. Both vehicles react to the same track defects (e.g., at 6,500 m and 9,000 m); however, the 122Nb produces isolated, very high peaks reaching up to 1.6 m/s^2. Despite the generally higher overall vibration level in the 805NaND tram, the 122Nb model transmits track impacts in a very localized and abrupt manner, which may be perceived as harsh "bottoming out" on irregularities.

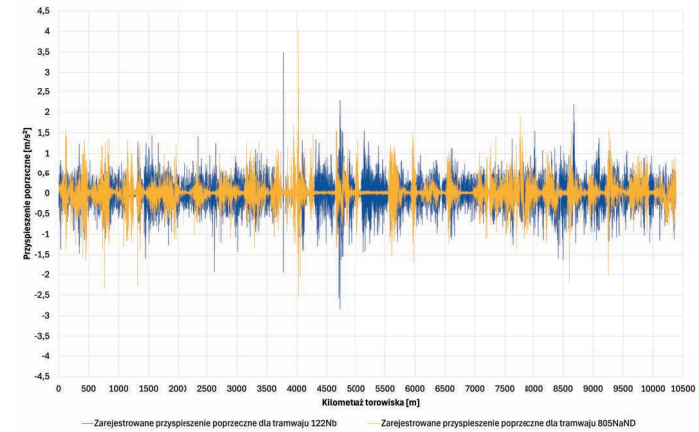
Figure **16** illustrates the lateral acceleration for Line No. 3 on the Motoarena – Heweliusza route. It can be observed that both vehicles exhibit abrupt acceleration spikes at similar points of the infrastructure. The largest peak



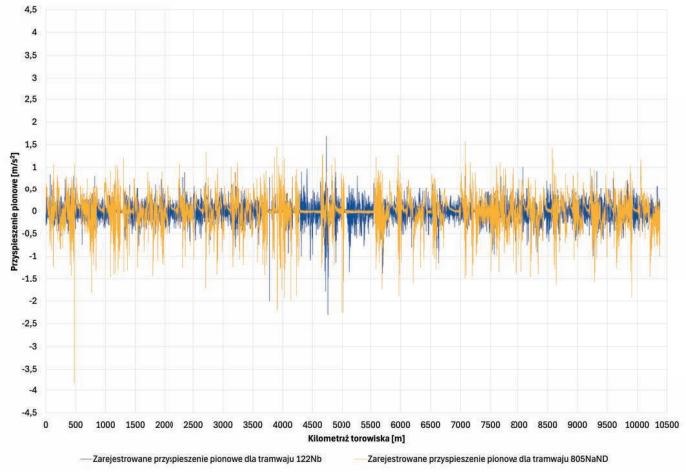
***14**. Lateral acceleration for Line No. 5 (Olimpijska P&R – Motoarena) for 122Nb and 805NaND rolling stock. Source: own work based on data [36]*



***15**. Vertical acceleration for Line No. 5 (Olimpijska P&R – Motoarena) for 122Nb and 805NaND rolling stock. Source: own work based on data [36]*



***16**. Lateral acceleration for Line No. 3 (Motoarena – Heweliusza) for 122Nb and 805NaND rolling stock. Source: own work based on data [36]*



***17**. Vertical acceleration for Line No. 3 (Motoarena – Heweliusza) for 122Nb and 805NaND rolling stock. Source: own work based on data [36]*

occurs around the 4,000-meter mark, where the 805NaND tram reaches 4.0 m/s^2 and the 122Nb model approximately. Throughout most of the route, the 122Nb vehicle maintains vibrations within a narrower band than the 805NaND. The infrastructure of this line possesses numerous track geometry defects, which the 805NaND vehicle tolerates much worse, generating lateral accelerations that are hazardous to both passenger comfort and vehicle stability.

The vertical acceleration shown in Figure **17** exhibits massive vertical impacts at the very beginning of the route, where the 805NaND vehicle records a drop in acceleration to a value of nearly – 4.0 m/s^2. This may be due to a track defect or a measurement error caused by the movement of the measuring device. Throughout the remainder of the route, both vehicles behave similarly, oscillating mainly within the 1.0 m/s^2 range. However, it can be observed that the 122Nb model features more intervals of low-amplitude vibrations, suggesting that its suspension provides better filtering of minor irregularities.

Figure **18** presents the lateral acceleration for Line No. 3 on the Heweliusza – Motoarena route, which, for most of the journey, remains within 1.0 m/s^2 the range. However, numerous shock-like peaks occur. Two areas of increased amplitude are clearly visible around the 6,250 m and 7,250 m marks, where peaks exceed 2.5 m/s^2. This may indicate abrupt entries into small-radius curves lacking adequate transition curves. After the 10,000-meter mark, there is a sharp increase in jerks, with a negative peak reaching nearly – 3.0 m/s^2. This value is extreme and highly perceptible to passengers. For the Heweliusza – Motoarena section of Line No. 3, measurements were conducted exclusively using the 122Nb rolling stock.

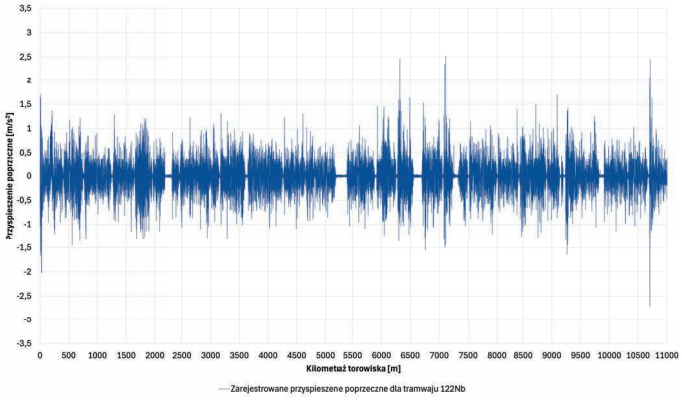
The vertical acceleration shown in Figure **19** is relatively low and stable, remaining for the most part within the range. This indicates effective damping of high-frequency vibrations by the bogie suspension system. Similar to the lateral plane, abrupt impacts occur. The most significant of these is observed around the 9,250-meter mark, where the negative acceleration exceeds – 1.3 m/s^2, followed by a positive rebound. Characteristic gaps in the signal are visible (e.g., around 5,300 m), which may result from the vehicle's temporary standstill or a lack of data registration at those points.

Summary

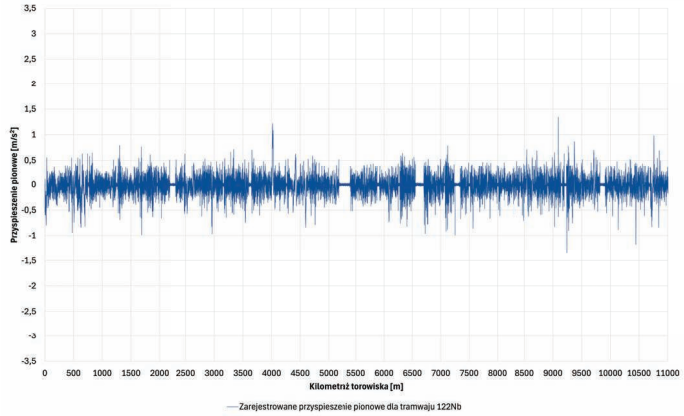
The conducted analysis of lateral and vertical acceleration profiles in both tram systems allows for the formulation of conclusions that extend beyond the simple identification of point-specific track defects, highlighting the complex interactions between rolling stock type and the geometry and maintenance condition of the infrastructure. In Olsztyn, it was observed that despite the relatively new infrastructure, Line No. 1 generates drastically higher accelerations (lateral peaks for the Durmazlar Panorama reaching from to) compared to Line No. 4, where amplitudes rarely exceeded. This indicates progressive degradation of track geometry on selected sections (e.g., 2,100 m and 6,800 m), manifesting as severe bogie hunting in vehicles with lower lateral stiffness.

In Toruń, the analysis of the narrow-gauge system (1000 mm) revealed that the older Konstal 805NaND rolling stock tends to generate a denser band of high-frequency vibrations. Conversely, the modern Pesa Swing 122Nb units transmit irregularities in a very localized and abrupt manner, with vertical peaks reaching. This suggests that the stiffer suspension of modern vehicles, while beneficial for stability at higher speeds, may transmit infrastructure defects – such as dipped joints or worn turnouts – in a "harder" way. This is confirmed by recurring peaks observed in both vehicle types at the same locations (e.g., 2,750 m and 6,750 m on Line No. 5).

Comparing both cities, it can be concluded that the Solaris Tramino S111O model is characterized by the most versatile damping properties, maintaining stability even in areas where other vehicles recorded vibrations threatening the comfort of standing passengers. In summary, the obtained results prove that the mo-



***18**. Lateral acceleration for Line No. 3 (Heweliusza – Motoarena) for 122Nb rolling stock. Source: own work based on data [36]*



***19**. Vertical acceleration for Line No. 3 (Heweliusza – Motoarena) for 122Nb rolling stock. Source: own work based on data [36]*

dernity of the rolling stock alone does not guarantee high ride comfort without rigorous maintenance of track geometry parameters. Furthermore, accelerometric measurements serve as an effective method for precisely identifying sections requiring urgent leveling and tamping. Table **2** presents a comparison of the maximum acceleration values.

Tab. 2. *Comparison of maximum lateral and vertical acceleration values for the tested rolling stock types*

City	Track gauges [mm]	Tram type	Maximum lateral acceleration [m/s2]	Maximum vertical acceleration [m/s2]	Dynamics notes
Olsztyn	1435	Solaris Tramino S1110	1.51	0.85	Maximum comfort, stable ride
Olsztyn	1435	Durmazlar Panorama	5.52	1.22	High lateral peaks – hunting
Toruń	1000	Pesa Swing 122Nb	1.28	1.64	Sensitivity to discrete track defects
Toruń	1000	Konstal 805NaND	1.45	1.51	High frequency of excited vibrations

Source: own work

Future Research Directions

Based on the obtained and filtered acceleration waveforms, it is possible to proceed to the evaluation of ride comfort. To this end, the next step is to determine comfort indices based on vertical and lateral acceleration values, calculated in accordance with current guidelines and standards. The analysis of comfort indices enables a comparison of individual tram route sections and an assessment of the impact of track surface condition on passenger travel conditions.

The determined comfort index values can be compared with the results of the acceleration peak location analysis, allowing for the identification of sections requiring special attention in the infrastructure maintenance process. Further analyses may also include a comparison of results between different types of tram rolling stock and track gauges, which will enable an assessment of the influence of these factors on the level of ride comfort. ◄

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