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POSSIBILITIES AND CONDITIONS OF APPLICATION OF THE KARLSRUHE MODEL IN SELECTED TRAMWAY SYSTEMS IN POLAND

Abstract

The article presents the problem of the possibility of adapting the Karlsruhe model in selected three tram systems in Poland. In the first part of the work, there are discussed: the genesis of the model and the possible technical-technological and organizational solutions in the field of tram-train system operation. There have been also identified: the barriers that obstruct the full integration of typical tram and railway systems, taking into account legislative, organizational and technical conditions. The second part of the article is devoted to the analysis of preliminary projects for the implementation of the tram-train system in selected Polish cities. The analysis was preceded by a short systematization of examples of historical solutions combining rail and tram transport systems. The proposals for the application of the Karlsruhe model quoted in the paper, showed that there is a relatively low level of advancement of this model and it is not included in the overall transport policy of the discussed cities. Actions that aimed at improving and increasing the attractiveness of tram transport are focused on the development of the classical system.

Keywords: tram-train system; public transport; trams, regional railways
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Introduction

The integration of collective transport in the agglomeration area and its suburban areas may contribute to the expansion of cooperative relations between them and the creation of a common public transport system. Typically, these activities focus on the extension of the impact of urban transport and its connection with

transport systems of a wider reach (e.g. with regional transport) and with other modes of transport. This issue also concerns the implementation of improvements of organizational and managerial nature, e.g. coordination of timetables, implementation of a uniform information system on transport services and the introduction of a common tariff.

The integration of collective transport in the agglomeration area may also concern infrastructural and technical-technological solutions. An example of such a solution that improves public collective transport is the Karlsruhe system, which enables the creation of an integrated public transport system based on tram transport. An unquestionable advantage of the system is the combination of tram transport serving the most important intra-city relations with the suburban transport, while using the potential of local railway lines. The aim of the article is to examine the possibility of using local railway lines in suburban areas of selected Polish cities and their inclusion into the tram system. In connection with the progressing development of individual motorization and the deepening infrastructure and organizational problems in public transport, it is necessary to implement improvements and coordinate the functioning of transport, which is why the problem is important for the future development of cities and agglomerations. In Poland, all currently operating tram systems are based on a classic tram. Although numerous investments are being implemented to develop tram systems in Poland, but none of them are concentrated on the tram-train solutions. The article presents the genesis and functional types of the system and describes the first historical attempts to connect rail and tram in Poland. Then, on the example of three urban centers with varying degrees of tram network development – Gdańsk, Kraków and Wrocław, case studies about possibility of implementing the Karlsruhe model, were carried out. These are examples of cities where contemporary studies have been made on the possibilities of implementing the model, and on this way those cities were chose to analysis. The research hypothesis is that the rail-tram system allows rational use of railway infrastructure around cities and enables the creation of new direct connections having a significant impact on the functioning of public transport systems in cities.

1. Review of the literature on the rail-tram system

The rail-tram system can be treated as a modern system of passenger collective transport combining the operational features of the tram and train (usually electric traction units) and properties in terms of infrastructure and transport organization rules. This is reflected in the specificity of the rolling stock – a "two-system tram" – a vehicle that can move both on tram tracks (in the cities) and on railway tracks (in suburban areas) (Kraśkiewicz, Oleksiewicz, 2016). The "tram-train" system is defined as a hybrid solution that combines different types of transport services. It is usually emphasized that the system "tram-train" enables to create direct connections between the regional (suburban) area and the city center. In the city, the system uses tram tracks and operates in accordance with tram regulations. Outside the cities, conventional rail tracks are used and traditional rail rules apply (with additional

requirements). One of the main goals of implementing the "tram-train" system is to maximize the use of existing infrastructure (Naegeli, Weidmann, Nash, 2012).

The creation of the rail-tram system results directly from the favorable development trend of tram transport in cities and the need to extend its reach to dynamically expanding suburban areas around cities that are characterized by growing transport needs. On this way, it is possible to improve the transport service of suburban areas and improve it by designing a direct line system from the city center to the suburbs. At the same time, the necessity to change between transport modes, which is often burdensome for passengers, and entails lengthening the total travel time and at the same time contributes to reduce the attractiveness of public transport, is eliminated. The issue of effective utilization of the potential of existing track infrastructure, especially railway infrastructure, is not without significance. The rail-tram system is predestined in a special way for large urban centers with a developed tram network and surrounded by a dense network of railway lines with low passenger transport and low profitability. As a result, the planning of new routes takes place without the process of designing new tram lines from scratch (Kraśkiewicz, Oleksiewicz, 2015a).

The genesis of the rail-tram system is inseparably connected with the German city of Karlsruhe, which already in the 1950s began to show great attention to environmental issues. Less than 40 years later, Karlsruhe, a city with a concentric street system, had to face with a serious communication challenge resulting from the progressive domination of individual car transport. Urban characteristics of the city and its financial problems significantly contributed to the abandonment of the construction of the subway or rapid urban railway system. Initially, it was decided to extend the existing tram infrastructure, giving off almost 80% of the tracks from traffic (infotram.pl, 2019a). In order to limit the negative impact of transport on the natural environment and to create an integrated and flexible collective transport system, a number of traffic analyzes were carried out, the results of which proved the possibility of using light tram vehicles on existing, unused or poorly used railway lines. Including railways into the urban tram network system, a consistent transport system was created based on the interoperability of these two modes of transport (Maternini, Ricardi, Cadei, 2014). Combination within one system, the regional rail with long station spacing and relatively high journey speeds up to 60 km/h and classic urban tram with many stops and journey speeds of about 25 km/h, makes it possible to offer the direct rides from the suburbs into the pedestrianized main street in the heart of the city. (Topp, 1998). The "Karlsruhe Model" developed in this way (or "tram-train system" – a rail-tram system) is based primarily on the use of modified tramway vehicles that are able to run on the standard tram tracks as well as local railways. It is also connected with changes in the scope of infrastructure consisting of its technical modification, connection of tram tracks with railway and construction of new stops in suburban areas (along railway lines) (Kraśkiewicz, Oleksiewicz, 2015b). Adaptation of vehicles to supply voltage of different heights or its diversification through the additional use of the internal combustion engine, makes it possible to improve the flexibility of tram transport (Luvishis, 2010). The combination of the advantages of the regional rail with the technical capabilities of the tram enabled the expansion of trams from

the city center to suburban areas, thus creating new direct connections with high frequency of running vehicles. At the same time it is necessary to reorienting the bus line system consisting on cancelling parallel lines with the railway line and creating the new perpendicular lines (Hasiak, Richer, 2012).

2. Conditions of using the rail-tram system

Over the years, the Karlsruhe model has undergone a profound evolution. Solutions applied in the field of the "tram-train" system are in every detail adapted to the individual specifics of transport markets. In addition to Karlsruhe, the rail-tram system was implemented, among others in Chemnitz, Kassel, Mulhouse, Nordhausen, Saarbrücken, Sheffield and Zwickau (the characteristics of these systems are shown in Table 1). In technical and organizational terms, the following types of two-system tram systems can be distinguished (Beim, 2017):

- With mixed tram and train traffic, where the range of tram transport is possible to be extended by using local railways (Karlsruhe) or by means of a tram, direct relations from suburban areas to city centers deprived of tram transport (Saarbrucken) are sought;
- With the exclusive traffic of trams on railway tracks, which were included in the tram system, maintaining the "railway" traffic organization on them (Sheffield);
- With mixed traffic of trams and light trains (e.g. rail buses) which, in order to improve the level of transport service, serve the city center by moving on a tram track (Zwickau).

Table 1. Characteristics of selected two-system tram systems

City	Characteristic
Chemnitz	The beginnings of the two-system tram are directly connected with the comprehensive modernization of the tram infrastructure, carried out in stages since the 1990s. In one of its stages, a city tram network was connected in the Altchemnitz district with the local railway line to Stollberg, which was electrified with 750V. In the following years, the two-system tram lines were directed to Burgstädt, Mittweida and Hainichen. The system consists of four lines operated, inter alia, by the Vossloh Citylink and Stadler Variobahn hybrid trams.
Kassel	Two-system trams were created as a result of the extension of the tram transport range to suburban areas. In this way, a regional tram network was created, consisting of three lines with a total length of about 184 kilometers. Trams move along traditional tracks in Kassel, and in suburban areas along railway tracks. The service of the two-system tram line includes, among others, 28 Alstom RegioCitadis wagons, 18 of which are hybrid trams, adapted to power from the rail and tram network, and the remaining 10 are trams additionally equipped with combustion engines. These wagons have a possibility to drive on the sections without traction network.
Mulhouse	The two-system tram line is an element of a tram system consisting of four lines. This line is suburban and has about 22 km (of which 17 km runs on railway tracks). The task of the line is to connect Gare Centrale with the city of Thann, and its service is directed by Siemens Avanto trams. Trams run every 30 minutes.

City	Characteristic
Nordhausen	Two-system trams run from 2004. The system was created thanks to the construction of a link between the tram tracks and the tracks of narrow-gauge railway station. The tram-train system is based on the tram line No. 10, whose route leads from the Krankenhaus to Ilfeld Neanderklinik. The line is operated by Siemens Combino Duo electric-combustion trams.
Saarbrücken	The beginnings of the two-system tram are related to the overturn of tram transport liquidated in the 1960s. In order to start the „tram-train" system, about 5 km of the tram line was delimited in the city area and the railway line to the French town of Sarreguemines was used. Nowadays, the system runs as a transgranic line from Sarreguemines via Saarbrucken to Lebach. This line has about 44 kilometers. The Bombardier Flexcity Link tram rolling stock used is a railway vehicle traveling on railway tracks and reinforced tram tracks.
Sheffield	The „tram-train" line belongs to one of the four tram lines of the Sheffield Supertram system. It was established in 2018. Trams run from the center of Sheffield to the nearby town of Rotherham, using the so-called „Sheffield ring road", which for the needs of the project was electrified with 750V voltage. On the route, the typical tram stops have been built, but the system is functioning with organizational rules for the railway lines. The line operates every 20 minutes and only Vossloh Citylink trams are used.
Zwickau	The two-system tram line is an extension of the railway line to the city center along the tram tracks. The local tram-train system is a reversal of the Karlsruhe model due to the operation of the train (RegioSprinter rail bus) on tram tracks. The introduction of this type of vehicles for servicing the city center required their adaptation to the requirements typical for standard trams (including the provision of switch systems). It was also neccesary to overcome the barrier associated with different track widths by building so-called „third rail". For example, to the center of Zwickau, with the use of tram tracks are operating the trains from Klingenthal.

Source: (own study based on: Kraśkiewicz, Oleksiewicz, 2016; Walther, 2000; infotram.pl, 2019a)

The coexistence of trains and trams on common railroads is the cause of a number of problems primarily of a technical and organizational nature, which are eliminated in various ways. Differences between typical tram and railway systems relate to method of power supply and traction voltage, different construction of railway and tram trucks, gauge of rolling stock and infrastructure, height of floors in vehicles and safety of getting on and off the vehicle due to differences in the height of platforms (Dąbrowski, 2014). Examples of differences between railway and tram systems in the context of legislative, organizational and technical conditions are grouped in Table 2.

The occurrence of these differences on many levels makes the investment in the system of a two-system tram appear more cost-intensive in relation to the construction of classic railway or tram lines. Discrepancies in costs result primarily from the need to consider and individual design of technical and organizational details and to develop common standards in the field of transport services. The technical differences in the construction and technological advancement of the rolling stock have the results directly in the cost of its purchase. In depending on the specification and adopted operating parameters of the two-system tram system (e.g. the need to use hybrid tramway vehicles with two power sources, due to tram traffic along unelectricized railway lines), that costs significantly exceeds the cost of purchasing traditional vehicles. An important economic problem of the operation of two-system trams are also issues related to the costs of access and maintenance of railway

infrastructure. Lack of uniform standards for "tram-train" systems, dictated by their strict adaptation to the specifics of a given transport service market, means that eliminating the differences discussed above, requires individual designing of most details (Beim, 2017).

Table 2. Differences between the railway and tram system on the background of legislative, organizational and technical conditions

Conditions	Examples of differences between a railway and tramway system
Legislative	• Different requirements related to the process of admission of a tram and train to operation;
Organizational	• Ensuring disabled people access to railways and trams due to differences in platform height and floor in vehicles; • Qualifications of employees driving vehicles (in the case of a two-system tram, it is necessary to have both rights – to drive tram and train); • Access to infrastructure (in the case of railways, it depends directly on the infrastructure manager);
Technical	• A different construction of track intersections and vehicle wheel profiles; • Track width (in case the trams are run on tracks with a narrow track gauge – eg. 1000mm, in relation to the 1435mm rail gauge typical for the rail); • Roll gauge (from 2.2 to 2.4 m for trams compared to over 2.8 m for trains); • Infrastructure gauge and differences in the height of platforms (tram platforms are usually low platforms, fully adapted to low-floor rolling stock); • Different parameters characterizing passive protection of vehicles before impact (durability of the vehicle's construction); • Traffic control systems (in the case of trams, they are coupled with street traffic lights, in the case of railways the control is based on the line blocking systems and controlled from the control room by the traffic controller); • Power supply systems (trams are usually supplied with a constant voltage of approx. 600-750V, while the railways can be supplied with either constant or alternating current of different voltage or operate as non-electrified lines).

Source: (own study based on: Kraśkiewicz, Oleksiewicz, 2015a; Beim, 2017; Durzyński, Pachołek, Cichy, 2018)

3. Projects of a two-system tram in Poland

Rail and tram systems, although based on similar technology, in the vast majority function as two separate, non-integrated organisms. As a result, each of these systems is characterized by separate and independent regulations defining organizational, legal and technical standards. Currently none of the 15 tram systems operating in Poland have "tram-train" lines. However, in the rich history of this mode of transport in Poland, there are some examples of solutions combining individual elements of the railway and tram (Walther, 2000). A brief description of these solutions is presented in Table 3.

Table 3. Applications in tram systems of railway solutions

Tram system	Characteristics of the system with elements of railway type solutions
Upper Silesia	• The development of the narrow-gauge tram network in Gliwice was treated as an extension of the narrow-gauge railway goods system operating in Upper Silesia since 1851. Both trams and trains moved along rails with the same track gauge of 785mm. Thanks to this, it was possible to link both systems, thus enabling the movement of freight trains in the inner city area along tram routes.
Koszalin	• In 1913, the tram line from Koszalin to Mielno was inaugurated and then it was extended to Unieście. The infrastructure of Small Steam Train (Mała Kolej Parowa), between Mścice and Mielno, was used to implement this project. It was also adopted to the tram traffic. Trams of the „beach" line ran every 20 minutes. At the same time, the movement of freight trains continued on this route. The beach rail system from Koszalin to Unieście based on the operation of tram vehicles is very often recognized as the progenitor of the Karlsruhe Model.
Szczecin	• Established in 1949, the plan of connecting the railway system with the tram system was a response to the growing transport needs in the districts of Stołczyn and Skolwin, resulting from the development of plants located in this area (steel mills and paper mills). Due to the lack of financial resources, the construction of a new tram line was considered on the use of the existing two-track railway line to Police. It was assumed that one train track would remain for the movement of freight trains and the second one would be dedicated to trams after route electrification and the addition of platforms. The route number 6 from Gocław was planned to run to Police. • In the mid-1950s, an internal tram line (Nabrzeże Ewa – Bytomska Street) started operating at the railway stations leased from PKP by the non-electrified railways located in the area of the Szczecin port. Initially, it was served by Herbrand vehicles with batteries and then by a L-type tram powered by an internal combustion engine (placed in the trailer). This solution can be referred directly to the „tram-train" system projects in Kassel and Zwickau.

Source: (Gołubicki, Kasprowiak, 2011; Klassa, 2018; Soida, Danyluk, Nadolski, 2010; Grochowiak, 1999)

The above examples, although very similar, did not fully reflect the contemporary essence of the tram-train system. The first attempt to introduce two-system trams was made at the end of the 1990s in Kraków. For the trial of tram travel, along the tracks of the Kraków railway junction, the Konstal 105NT tram wagon was coupled with the Kolzam MS-W-01 rail bus (Czyczuła, Raczyński, 2000). The test of tram vehicle on railway tracks (including routes in Niepołomice and Wieliczka), was proved the possibility to tram ride on the railway tracks. At the same time, there was emphasized the necessity to adjust the power supply of the tram to the 3 kV railway voltage and the construction of links between the tram and railway tracks. It was also considered that, there is the opportunity to adopt the tram rolling stock to new tasks (Czauderna, 1998). The conducted tests were reflected in the concept of an integrated rail transport system for Kraków, in which full integration of the tram and railway network with the use of the Karlsruhe model was assumed. As a result, trams would move on lightly loaded railway lines: from Bieżanów to the market square in Wieliczka and to Niepołomice via Podłęże, from the vicinity of the current Łagiewniki loop to Skawina, as well as from Mydlniki to the airport in Balice. Tram-train connections were also planned in the area of Nowa Huta and Batowice

(Czyczuła, 1999). According to the assumptions, two-system trams would start or end the run on tramway tracks (or railways adopted to the exclusive tram traffic) and the railway infrastructure would be used for transit (including the addition of new tram stops) (Czyczuła, 2000). Plans to implement the "tram-train" system were also reflected in the tender for purchasing modern trams announced in 2000, which included also a two-system rolling stock. The final order for two-system vehicles was not realized due to the resignation of the contractor – the Alstom company, which was selected through the tendering procedure. In the following years, efforts to improve the tram system focused on the project of the Kraków Fast Tram from Krowodrza Górka to Kurdwanów (Kołodziej, 2010).

Proposals for the implementation of the "tram-train" system also apply to the urbanized area of Wrocław, together with the use of the potential of secondary railway lines existing in this area. The first mention of the possibility of using local railway lines by Wrocław trams appeared in the late 1990s. In the following years, proposals to take over railway lines to service trams went through quite a significant evolution, becoming a research subject at many scientific conferences organized by the Wrocław University of Technology. According to the initial assumptions quoted in the conference materials, trams would run, among others, to: Jelcz-Miłoszyce, Oborniki Śląskie, Siechnice, Sobótka, Trzebnica and Wołów. The places of contact of the typical tram and rail system would probably be tram loops Kowale, Poświętne and a new loop at Wroclaw Psie Pole station (Makuch, 2016). The most current concept of the "tram-train" system for Wrocław, presented in 2012 during the Tram Investments Forum, is the so-called Project "MeTram" by W. Zdanowski, according to which two-system trams would run on three lines (Kokoszkiewicz, 2013):

- "3+" from the Wrocław Leśnica do Siechnice station (with tram traffic only on the Wrocławski Park Przemysłowy section – Krakowska Street);
- "7+" from Oborniki Śląskie to Kobierzyce (with using tram tracks from the Poświętne loop to Karkonoska Street);
- "21+" from Biskupin to Pracze Odrzańskie (with traffic on tram tracks only on the section Rondo Reagan – Robotnicza Street).

The concepts of the two-system tram also concerned the Wrocław district of Bielany and the Otłaszyn housing estate (transport-publiczny.pl, 2019). The largest investment in urban transport in Wrocław, was so-called "Tramwaj Plus" project, which was included the rapid tram system (classic with increased parameters) from the city center towards the districts: Gaj and Kozanów and to the Municipal Stadium in Pilczyce. The project also assumed the modernization of approximately 40 km of existing tracks and the purchase of a new Skoda 19T rolling stock (Sielicki, 2012). In the assumptions regarding this project included in the study entitled "Integrated rail transport system in Wrocław and the Wrocław agglomeration" from 2006, it was noted that the "Tramwaj Plus" lines could also function outside the city borders. For this proposal, it would be neccesary to use existing railway lines whithout a regular passenger traffic. In the above-mentioned initial plans for the implementation of the "tram-train" system in Wrocław, it was also assumed that the dual-system tram lines will ultimately take on the character of priority lines. On this way they would be a continuation of the "Tramwaj Plus" project. Although in many studies, recalling the urbanization and organizational arguments,

the legitimacy of implementing the "tram-train" system was pointed out, further work in this area was suspended. It was pointed out that there are some problems due to difficulties in the approval and operation of rolling stock and to the lack of provisions regulating the mixed traffic of trams and trains. At the same time, the maintenance of the separation of the rail and tram system was indicated as a more beneficial solution (Makuch, 2016).

Proposals for the extension of tram systems based on railway solutions also concerned Gdańsk. The implementation of the "tram-train" system would be based on the use of so-called Pomeranian Metropolitan Railway lines and a fragment of occasionally used 249 railway line from Gdańsk Główny station to Brzeźno and Nowy Port (which was the one of the elements of the Tricity fast suburban train system). According to the originators, two-system trams would run from Nowy Port to Ujeścisko through Kliniczna Node, next by the planned tram route "South Gdańsk-Wrzeszcz" and Morena district. The second line would start from Ujeścisko via Brętowo and Strzyża to final stop on the route in Oliwa. Sections of the route between the Nowy Port, and the Kliniczna Node and between stops Brętowo PKM and Strzyża PKM, trams would overcome the railway line, and on the other sections – using the infrastructure of a typical tramway line (infotram.pl, 2019b). According to the guidelines of the "Study of Conditions and Directions of Spatial Development of the City of Gdańsk", the introduction of trams on the so-called Pomeranian Metropolitan Railway line, will be possible in the event of changes in regulations governing rail traffic (urban planning of the City of Gdańsk, 2018).

The above three projects of implementing the tram-train system in Poland, fully reflect its contemporary technological essence. They were the subject of studies on improving and organizing traffic in the area of cities and surrounding suburban districts. In any case, they could be a real opportunity to improve the attractiveness of the public transport system and the level of its integration. However, it is very important that these projects contain only a general assumptions, which, moreover, were not explicitly included in the studies and transport plans of these cities. Considering the technical organizational and legislative conditions, it should be stated that in the near future these cities will strive to expand and improve the functioning of classic tram systems.

4. Discussion on the feasibility of introducing a rail-tram system in Poland

Adaptation of the Karlsruhe model in selected tram systems in Poland can be an opportunity to improve the functioning of transport systems in large cities, primarily meeting the growing transport needs from suburban areas to the very center. It requires precise specification of the division of transport tasks and the solution of a number of problems resulting from the coexistence of trains and trams on common railroads. The basic issue that makes it difficult to undertake advanced project activities including the rail-tram system is the lack of provisions clearly defining the scope of the possibility of running a common tram and train movement.

At the same time, it should be pointed out that the specificity of local transport markets in Polish cities, as in the foreign examples mentioned in the paper, would

require individual design of the rail-tram system. This applies in particular to technical and technological solutions in the area of track infrastructure, construction of platforms and traffic control systems and the use of modified, specific rolling stock. What is important, it would have to be a vehicle fully adapted to the individual characteristics of the tram-train system, taking into account the different construction of vehicles and differences in range of gauge and power supply systems. All these factors make the investment in the tram-train system appear to be highly cost-intensive in relation to the construction of classic systems.

The implementation of the tram-train system would also require the necessity to regulate organizational and legislative issues related to the process of rolling stock admission into operation. It would be also necessary to regulate issues connected with the granting access and issuing a permit to conduct traffic on railway tracks, which are directly dependent on the entities managing the infrastructure.

Conclusions

The Karlsruhe model combining the regional rail and tram system enables the increase of the range and the introduction of trams to service suburban areas. In order to meet the growing transport needs from suburban areas to the city center, the "tram-train" system allows for the construction of new direct connections. The combination of tram and train operating characteristics requires the use of modified rolling stock and implementation of technical and technological improvements in the field of infrastructure. The use of the Karlsruhe model makes it necessary to eliminate the legislative, organizational and technical differences between the typical tram and rail systems. Direct adaptation of the model to the specificity of transport markets results in the fact that the examples of functioning rail-tram systems cited in the article are based on similar, but not identical, technological solutions that required individual design.

Currently, none of the 15 tram systems operating in Poland, includes solutions in the Karlsruhe model. Although tram and railway transport systems function as two separate organisms, in the history of development of these means of transport in Poland, examples of solutions combining selected elements of railways and trams can be found.

Contemporary proposals for the implementation of the "tram-train" system concerned, among others, Kraków, Wrocław and Gdańsk. In each of the cases described, the proposals for the implementation of the "tram-train" system were the subject of many studies and analyzes. In spite of many attempts, they were ultimately not specified in the form of projects. They were also not clearly stated in the studies and assumptions of transport policies of these cities. The deficiencies in the regulations governing the joint rail and tramway traffic as well as the high purchase costs of the rolling stock (which would have to be fully adapted to the individual specifics of the transport market) should be considered barriers to the implementation of the system. The conditions mentioned in the paper allow to state that in the Polish tram systems the Karlsruhe model will not be widely used.

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