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A numerical analysis of the contact stress distribution and physical modelling of abrasive wear in the tram wheel-frog system

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ABSTRACT

The condition of track infrastructure has direct influence upon the safety and comfort of tram transport. The sections of tram tracks which demand the closest attention are tram turnouts with frogs as integral elements. The purpose of this work was a thorough analysis of the most significant factors that influence the degradation of tram turnout frogs. Numerical simulations of contact stresses distribution in the tram wheel-frog system were performed under this research. It also included physical modelling of abrasive wear and operating tests in the real working conditions of frogs. On the basis of the results, the most important causes of the fast wear of tram turnout frogs were defined.

Investigations performed in the operating conditions showed that tram frogs are the elements which are the most exposed to fast wear and withdrawal from usage. It was also shown that the increment of wear in the grooves of common crossings (frogs) was ca. 0.37 mm/month. On the basis of the numerical calculations it was observed that the values of contact stresses depend on both the shape of the wheel flange and load value. The distribution of contact stresses in the plane transverse to the track axis is not elliptical, contrary to Hertz's theory. The abrasive wear resistance tests proved that slippage is the factor with a major impact on the intensity of frogs' abrasive wear. The second, and also significant factor worsening tribological durability is increase in the load value.

1. Introduction

Tram transport is an important link in mass passenger transport in many urban environments. Fluent urban transport improves the quality of citizens' lives, increases entrepreneurial attractiveness, and contributes to the reduction of car flow in cities, which has a measurable influence on the environment. After the tide of liquidations of tram systems after World War II in the USA and Western Europe, a real renaissance in tram communications is occurring at present. Due to its undeniable values, this transport system has been observed to be developing rapidly in many urban areas around the world in recent years. More and more complex and expensive modernisations are being conducted on tram networks, and new tram lines are also being built.

The safety and reliability of transport are significant elements of modern tram communication functioning, and they depend on the condition of the track infrastructure. Its quality determines tram speed and influences noise and vibration emissions to the surroundings. The worsening condition of track infrastructure, including tram turnouts, has a direct influence upon the safety of tram transport [1].

Turnouts represent trouble spots in tram track sections. Tram turnouts are particularly exposed to the increased dynamic interactions connected with the change of the ride direction and discontinuity in a stretch of rails. In large urban environments the intensity of traffic is very high, which causes fast wear of the tram turnout frogs. A turnout frog is an element of a tramway turnout which enables the wheels of a rail vehicle to ride through rail intersections. Degradation processes of tracks and turnouts are also affected by the technical condition of the tram rolling stock.

The load, slippage and properties of the materials used have a decisive influence on the wear in the wheel rail system [2–5]. The load imposed on a rail and caused by the pressure of the rail vehicle wheels, which is a function of tram mass, induces a specific state of contact stresses in the contact place of the material. These stresses may achieve high values and lead to a critical stress–strain state in the immediate vicinity of the contact area. In extraordinary cases of load, highest contact stresses often reach values which numerically exceed the yield point and the tensile strength limit of the material [4–6]. Places of the increased critical stress–strain state may be a source of subsurface cracks. They also contribute to the intensive abrasive wear. For these reasons, the materials used

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in these components must have appropriate mechanical characteristics which provide them with high operational durability [4,5,7,8].

In this study a thorough analysis of factors that influence the durability of tram frogs was attempted. For this purpose, numerical simulations of contact stresses distribution were conducted for the frog which contacts the tram wheel. The research also included physical modelling of abrasive wear, and operating tests in the real working conditions of the frogs. On the basis of the investigation carried out, the most important causes of the fast destruction of tram turnout frogs were defined.

2. Conditions of the interaction between the wheel tread and tram frog

Tram turnouts constitute a critical structure of the tram communication routes. They serve to connect two tracks, and in this way they enable change or maintenance of the former rail vehicle ride direction. A tram turnout is supposed to allow fluent and safe transport of the tram bogies [1]. Turnouts differ from each other in their geometrical arrangement (inter alia, radii of the diverging track arc) and strength parameters of constituents. Owing to their critical function in tram traffic, turnouts have to be characterised by reliability, durability and work safety. A diagram of a typical tram turnout is presented in Fig. 1.

One of the principal components of the turnouts is the frog, which allows the wheels of the vehicle to ride through rail intersections. The structure of the tram frogs and the technique of the rail vehicle's movement over the frog significantly differs from the solutions used in railroad transport. The frog of the tram turnout is manufactured as a block one with shallow grooves cut in it. It is made with block section 310C1 and welded with connecting rails made with block section 105C1 and grooved rails. A groove is cut to a depth of 12 mm. Frog entries are inclined 1:100.

Tram frogs are supposed to eliminate the problem of discontinuity in a stretch of rails in the tram turnout frogs. A tram wheel runs on the frog through the entry platform, then it rolls at the wheel flange instead of the wheel tread. This solution is aimed at providing continuous contact between the tram wheels and the railway track structure (Figs. 2 and 3).

Due to the relatively narrow tram wheel flanges, there is high pressure focused on the relatively small area at the bottom of the frog's grooves. The effect of this phenomenon is plastic deformation at the bottom of the grooves and intensive abrasive wear. Along with further degradation processes, the systematic deepening of grooves follows, which leads to the change of transport techniques in reference to the badly worn frogs. As a result of frog grooves deepening, wheels start to roll over the upper structure of the frog block. In this case additional dynamic interactions appear (discontinuity in a stretch of rails occurs). What is more, the discrepancy between the diameters of the rolling wheels connected by a common axle causes the occurrence of considerable increase of the slippage. The fast wear of tram frogs in large urban environments is also the consequence of their intensive use. ca. 15,000 rides of tram wheels are possible assuming that ca. 5–6 tram lines run this route in one week. The enumerated factors contribute to the intensive wear of frogs, which worsens traffic safety and is a cause of numerous derailments.

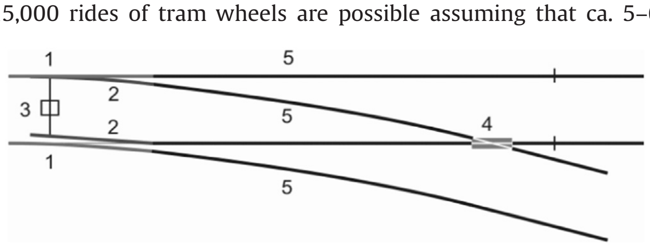

Fig. 1. Tram turnout 1 – switch, 2 – needles, 3 – point machine, 4 – frog, 5 – connecting rails.

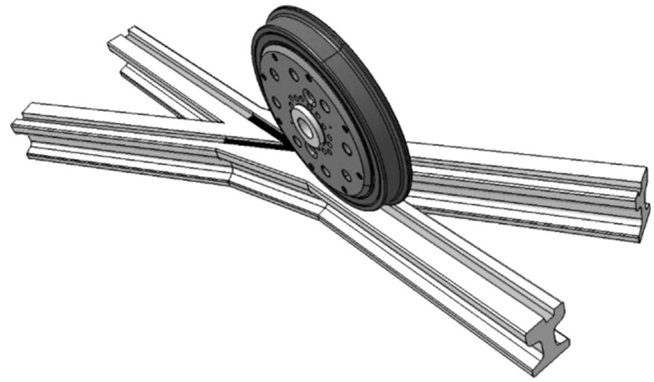

Fig. 2. Scheme of wheel transport over the tram frog.

There are vehicles with different rolling profiles of the wheels exploited on the examined tram network. These are T-type and PST-type profiles (Fig. 4). The PST profile is a so-called wearing profile, and was created as a result of long-standing observation of the T profile wear. These profiles differ from each other, first of all, in the width of the flange point, flange thickness, and rolling surface shape.

The outlines of the tram wheel flanges are changed in the service process. In consequence of the wear process the value of the flange height rises, while the value of the flange thickness decreases. Moreover, as the result of the wheel ride over the block frog, the flat surface of the flange point is subject to rounding. A change in the geometry of the wheel's rolling profile causes alteration in the wheel's contact with the rail, and the frog too. An example of a worn tram wheel's rolling surface profile is shown in Fig. 5.

Tram wheels are connected with each other with a common axle. During the wheels' ride over the shallow-grooved frog one wheel rolls with the rolling surface on the connecting rail while the second wheel rolls with the flange point at the bottom of a frog groove. A discrepancy between rolling radii causes longitudinal slippage, which is an effect of the difference in the developed lengths of the rolling wheels' rings rolling on both stretches of the track. The values of longitudinal slippage for a ride in the principal direction (along a straight line) may be determined by means of the following formula:

$$L = \frac{R_1 - \varsigma - R_2}{R_1 - \varsigma} \times 100\% \tag{1}$$

where:

L – value of the longitudinal slippage,
R_1 – rolling radius of the wheel rolling over the frog, m
R_2 – radius of the wheel rolling on the connecting rail, m
ς – coefficient dependent on the inclination of the entry platform.

Coefficient ς is an increment of the distance falling on a one wheel rotation caused by application of the entry platform, and is expressed by means of a formula.

$$\varsigma = \frac{s}{2\pi \cos \alpha \times R_1} \tag{2}$$

where:

s – length of the entry or exit platform, m
a – entry platform inclination angle
R_1 – rolling radius of the wheel rolling over the frog, m.