Tribological Aspects of the Wheel and Rail Interaction

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***Abstract*—For enhancing effectiveness of the wheel and rail operation, it is necessary to decrease probability of derailment, energy consumed on traction, maintenance expenses due to wear and other types of damage, pollution of the environment by friction modifiers, wear products, train accidents, vibrations and noise. All these factors, mainly depending on tribological properties of the wheel and rail contact zone are interconnected in the course of the train movement and vary under impact of various power and thermal loads. For retaining due tribological properties in various conditions of the wheel and rail interaction it is necessary to control these properties. In the work, on the base of new concept of the mechanism of variation of tribological properties of interacting bodies developed by us [George Tumanishvili, Tengiz Nadiradze, Giorgi Tumanishvili. A new Concept of the Mechanism of Variation of Tribological Properties of the Machine elements Interacting Surfaces. Chapter in the book Tribology in Materials and Manufacturing. IntechOpen, 2021. Pp. 131-150], the reasons of negative, neutral and positive friction and mild, severe and catastrophic wear are explained and the ways of providng due tribological properties of the interacting surfaces are identified. For enhancing effectiveness of the wheel and rail operation were developed ecological, heat resistant friction modifiers for the wheel and rail tread and steering surfaces and devices for their application that were tested in the laboratory and field conditions. The conditions of the wheel climbing the rail were also given definitive shape and the reasons of the rail corrugated wear, and ways for its decrease were revealed.**

Keywords—wheel, rail, tribology, third body

I. Introduction

Increasing speeds and axial loads of the modern railway transport is the result of achievements of the engineering art, where the role of tribology is essential, though it lags behind engineering in general [1]. Such indices of the rail trasport effectiveness as probability of the wheel climbing on the rail, energy consumed on traction, pollution of the environment by vibrations, noise, friction modifiers and wear prodcts, working resourse and maintenence expenses of the rail and friction brakes greatly depend on tribological properties of the corresponding contact zones. As it is specified in [2], for curved track a 33% reduction in the rolling resistance can produce a 13% reduction in total resistance, while for straight track a similar reduction produces a 3% reduction in total train resistance.

Vibrations and noise that are problems for the railway can be caused by many reasons: interaction of the wheel flange and rail lateral surface, non-roundness of the wheel, rail corrugations etc., but some aspects of this problem are not completely revealed [4].

The vague recommendations existent in the literature for prediction and control of tribological processes of the wheel, rail and friction brakes interacting surfaces are often the sources of various undesirable phenomena and wrong decisions about their prevention (railway accidents, increased energy consumption, environment pollution etc.). This also applies to selection of constructional materials and lubricants, optimal working modes according to various conditions, measures for perfection of operation of the wheels, rails and friction brakes.

In Figure 1 is shown a rail after the wheel climbing on it, where the scuffing trace is observed that is explained by the increased friction factor promoting a derailment [4, 5, 6].

Axial load of the train wheel often exceeds 25 t; contact pressure 3 GPa and nominal area of the contact zone reaches 1 sm2. Therefore, for the wheel movement is typical rolling with sliding. The wheel tread surface is of conical form and at its rolling on the rail in the contact zone with the rail are simultaneously interacting surfaces of the wheel diameters slightly differed from each other. But rolling is only possible on one diameter and on the other diameters rolling with sliding take place that causes additional shearing stresses in the contact zone. The wheel often moves on the rail in the mode of traction and braking at which its tread surface tends to slide on the rail and partial sliding in the contact zone can pass into full sliding. At interaction of the wheel flange and rail lateral surfaces the difference between the diameters interacting with the rail and value of the relative sliding increase sharply even without the traction and braking modes.

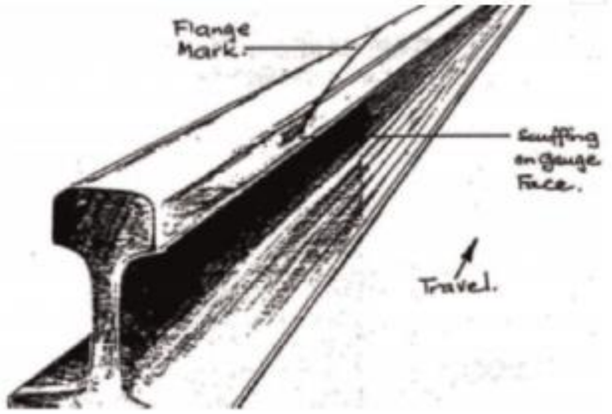


Fig. 1. The trace of the wheel climbing on the rail

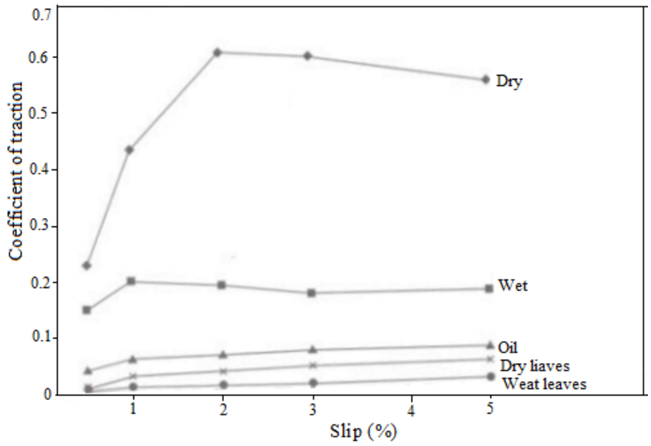


Fig. 2. Dependences of the friction coefficients on the relative sliding velocity

At modeling of the wheel-rail interaction, a friction coefficient is considered as a constant and known value. However, the results of many experimental researches show that in the wheel-rail contact zone it varies in the range 0.02-0.8 and it is influenced by many factors not all of them being known. This can become the reason of various unjustified decisions. For example: decrease of the distance between rails by 4 mm (at unchanged distance between rails) in the former Soviet Union in 1970-1980; lubrication of the wheel and rail tread surfaces and the wheel flange root (that plays the role of both, the tread and steering surfaces); at selection of the train movement mode consideration of insufficient quantity of parameters etc. All this is the reason of various negative phenomena.

Usually, the surfaces are covered with various types of natural and artificial coatings, which represent the components of the third body in the contact zone of the interacting surfaces. These surfaces are subjected to heavy power and thermal loads. This causes deformations of these coatings, their destruction, activation of the physical and chemical processes proceeding between them and the surfaces and generation of new coatings. Thus, during interaction of the surfaces, the processes of the third body destruction and restoration takes place in the contact zone continuously.

In fig. 2 is shown the dependences of the coefficient of friction on the slip ratio for different materials applied on the interacting surfaces [7].

At destruction of the third body on the separate micro asperities, they interact directly that leads to seizure. The results of laboratory tests showed that wear coefficient depended strongly on sliding velocity. The increase in the wear coefficient at increasing sliding velocity was explained by the change of wear type from mild to severe[8].

At rolling with sliding of heavy-loaded bodies, the most dangerous (dominating) kind of damage is scuffing. It arises at destruction of the lubricant film (the third body) and direct contact of bodies in extreme friction conditions. For prevention of this phenomenon, they try to minimize a sliding distance (structures of wheels and rails, dynamic characteristics of the track and a rolling stock, etc. must be improved) and to improve the tribological characteristics of the contact (to improve properties of contacting surfaces and applied lubrication). Necessary condition of scuffing is destruction of the third body and direct contact of surfaces. For formation of the third body are frequently used liquid lubricants. Consistent and solid lubricants are also used.

The wheels and rails are subjected to significant dynamic loads, transmitted from the car, that produce high stresses on the very small contact zone. Fig. 3 shows the static stress distribution at sliding at different sliding friction coefficient [9].

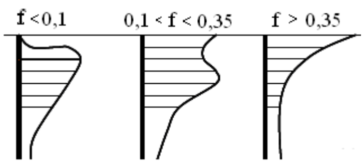


Fig. 3. Stress distribution at sliding at different sliding friction coefficient.

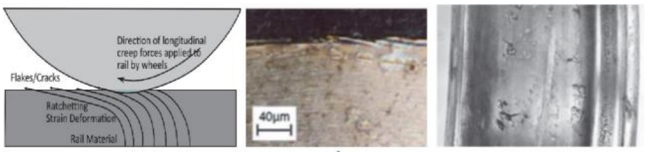
Maximum value of the shearing stress is in the subsurface area when coefficient of friction $f < 0.1$. The area of maximum pressure is shifted towards the surface when the shearing stress increases. There are two maxima: under and then on the surface when coefficient of friction $0.1 < f < 0.35$ and the maximum value of the shearing stress is in the subsurface area. When the coefficient of friction $f > 0.35$ the maximum value of the shearing stress is on the surface.

II. DEPENDENCE OF TRIBOLOGICAL CHARACTERISTICS ON THE DEGREE OF DESTRUCTION OF THE THIRD BODY

The third body is stable to the normal pressure. Increase of sliding velocity leads to increase of shearing stress, friction power and thermal loading of the contact that contributes destruction of the third body. For heavy loaded interacting surfaces is typical seizure, when continuity of the third body is destroyed in individual places and invasion of micro-asperities into each other in the contact zone and their close contact without the third body take place.

The wheel and rail contact zone are characterized by heavy operational conditions [10] (direct impact of the environmental conditions, high relative sliding and contact stresses) that enhances adhesive and fatigue processes. The unpredictable change of tribological properties - sharp increase of the friction coefficient and wear intensity, so called catastrophic wear are typical for them that is not properly studied yet [11] and whose signs are appearance of pits and scratches on the surfaces and transfer of the material from one surface on the other. As an example, can be cited interaction of the wheel and rail that occurs on: the tread surfaces during rolling, traction and braking; steering surfaces mainly in curves; flange root and rail corner at rolling, traction, braking and steering.

The shear deformation generated on the surface sharply decreases towards the depth and multiple repetition of such processes results in superficial plastic deformations, lamination and fatigue damage (Figure 4) [12, 13].



a b c

Fig. 4. The scheme of the surface plastic deformation (a); appearance of crack and lamination (b); appearance of fatigue pits (c).

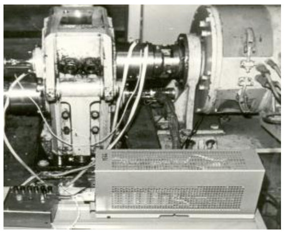
The friction forces between interacting surfaces (at lack of the third body in the places of actual contact) mainly depend on the total area of the seizure contacts. Displacement of the coupled places of surfaces relative to each other causes sharp increase of the shearing stresses and corresponding deformations (that considerably exceed the normal stresses and deformations), value and instability of the friction forces and rupture of the coupled places. This leads to increase of various kinds of damage that proceeds simultaneously with various intensity. Depending on seizure value, these deformations at multiple repeats can lead to lamination, fatigue destruction of surfaces, tearing off material from the contact zone and removal as wear product or transfer of the pulled-out material from one surface on the other and their adhesion (characterized for scuffing). It is possible in this case sharp change of roughness of these surfaces and development of the process of catastrophic wear – scuffing.

The experimental researches have shown that tribological properties (damage type and intensity, friction coefficient, vibrations, noise etc.) of interacting surfaces are especially sensitive to the relative sliding velocity and shearing stresses.

The experimental researches into the third body properties were carried out on the high-speed twin disk machine (Fig. 5) and on the twin disk machine MT-1 (Fig. 6) in the broad range of operational factors with the use of existing lubricants and ecologically friendly friction modifiers, developed by us.

In the field of railway simulation, it is a general assumption to consider the coefficient of friction as a known and constant value. This hypothesis is clearly not correct as many factors can change the friction coefficient.

The various dominant damage types, wear rates, and friction coefficients are typical for various relative sliding. In Figure 6 is shown dependence of the friction coefficient on the relative sliding and expected kind of surface damage. Three zones can be distinguished in Figure 4. In zone 1 and at the beginning of zone 2, deformations of the subsurface layers reach the maximum values, and the interacting surfaces undergo cyclic deformations. With the rise of relative sliding, the contact temperature gradually increases, decreasing viscosity of the third body [14] and the friction factor that reaches the minimum value. At full separation of the interacting surfaces by the third body, the tribological properties of the contact zone mainly depend on the properties of the third body, and they provide high wear resistance of the interacting surfaces and relatively stable friction coefficient.



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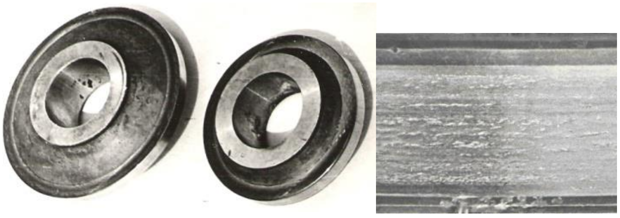

b c

Fig. 5. High speed twin disk machine (a), experimental pieces (b) and a working surface of the roller with traces of scuffing (c) at total speed of rolling 7 m/s, sliding speeds of 3 m/s, linear load 100 N/m

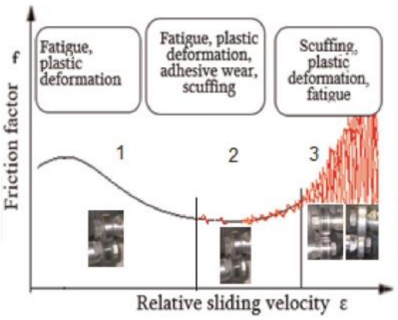

Fig. 6. Dependence of the friction coefficient (f) on the relative sliding (ε) and expected kinds of surface damage.

In zone 2 the separate small impulses of the friction moment and adhesive wear of low intensity correspond to destruction of the third body in the separate unique and multiple places. The first point marks of scuffing appear on the interacting surfaces and balance between destruction and restoration of the third body is observed, that stipulates the “mild” and “sever” wear [15]. In zone 3 destruction of the third body takes place in the narrow strips that pass then into whole area of interacting surfaces, the surface roughness changes correspondingly to working conditions (rolling speed, sliding rate, contact pressure etc.) resulting in rise of the friction coefficient, its instability, wear rate (reaching “catastrophic” wear), and scuffing.

Therefore, we have three stages of variation of the tribological characteristics of interacting surfaces (friction coefficient, roughness and wear): at continuous third body, at reversible discontinuous third body and at irreversible discontinuous third body. The first stage is characterized by minimal wear rate and change of roughness and stable friction factor. The second stage is characterized also by the minimal but slightly unstable friction coefficient, roughness, and wear rate. In terms of tribological characteristics, the stage 1, as well as stage 2 can be considered as the acceptable working conditions of the tribological system. In contrast to this, stage 3 is characterized by the sharp rise of the constant and variable components of the friction coefficient, wear rate (“catastrophic wear”), vibrations, and noise and operation in this zone is not admissible.

The signs of beginning of the third body destruction are instability of the friction (coefficient) moment, vibrations, and noise, and at visual observation in the laboratory conditions, the signs of scuffing are noticeable. Its prediction is possible with the use of the tables and graphs considering the given friction modifier, working conditions and environment properties, as well as the criterion of destruction of the third body [16].

III. Some features of wheels and rails interaction in the curves

In the straight, a wheel-set performs a zigzag movement close to the sinusoid, which is accompanied by creeping.

In curves, the inner wheel passes the shorter distance, which causes deviation of the wheel set axis from radial disposition. It leads to increase of the angle of attack, lateral force and rolling resistance of outer wheel of the front wheel-set of the bogie and promotes problems of wheel-flange climbing on the rail and derailment, squealing noise, wear of the wheel flange and gauge face of the high-rail and corrugations basically of the low-rail. In such conditions, for prevention of derailment and returning the wheel-set into initial position it is necessary that one of the wheels of the wheel-set slide on the rail in the longitudinal direction. There are many attempts to obtain radial position of the wheel-set [17, 18].

The movement of the wheel-set in the curve commonly leads to periodical advancing of the inner wheel relative to the outer wheel and the further return of the wheel-set symmetry axis near initial position by sliding of the wheel on a rail. That is the cause of periodic torsional deformations of the wheel-set axle and wear of the wheel and rail. The intermittent slipping of one of the wheels of the wheel-set can produce torsional vibrations of the wheel-set and longitudinal vibrations of the vehicle (that have been identified as flange noise [19]) and the respective wear of wheels and rails, like corrugation. In Fig. 7 is shown movement of a wheel-set in the curved track and a corrugated inner rail.

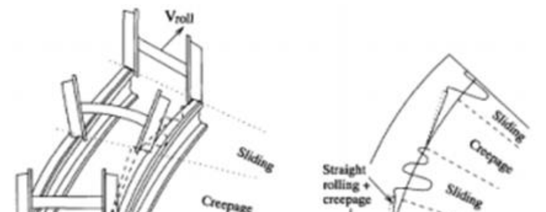

Fig.7. Movement of a wheel-set in the curved track and a corrugated inner rail [20]

The similar picture would be at movement of the wheel-set in the straight track with the wheels of different diameters or one wheel having ellipticity [21].

The researches have shown that a dominating type of deterioration of working surfaces for the given conditions is the scuffing. The high sensitivity and limited stability of used lubricants to the thermal loads have been also shown. The experimental researches have shown high sensitivity of the third body destruction to the sliding rate. For heavy loaded interacting surfaces is typical seizure. Certain part of micro-asperities of the heavy loaded interacting surfaces are in direct contact with each other causing their seizure and the remaining part interact with each other through the third body.

The smoothness of interacting surfaces is especially influenced by their velocity. At low velocity time of thermal impact on the surface part, depth of the heated layer and damage and amplitudes of variation of the friction force and noise are great in the actual contact zone. With increase the velocity these parameters decrease and at high velocities amplitudes of variation of the friction force and noise, as well as scales of individual damages of the surfaces and roughness decrease (when total rolling velocity exceeds 50-60 m/s the noise passes into high frequency whistle and at further increase of the velocity it exceeds the limits of human ear perception) [21], though high wear rate is retained. Thus, roughness of the surfaces of heavy loaded friction contact differs from their initial roughness and depends on their working mode.

Our experimental researches have shown that at the same friction modifier variation of the friction coefficient depends on degree of destruction of the third body: negative friction takes place at continuous third body; neutral friction – at partly destroyed and restorable third body, and positive friction – at progressively destroyed discontinuous and non-restorable third body.

It should be noted that various types of damage take place simultaneously and with various intensity in the heavy loaded contact and visually they are seen as dominant types of damage. The experimental researches have shown that the type of degradation of interacting surfaces mainly depends on the combination of the relative sliding velocity and shearing stress. For example, the main type of damage at low relative sliding is fatigue wear [13] (generation of cracks, plastic deformations and exfoliation), though adhesive wear takes place in parallel. Such phenomenon takes place on the rolling surface of the train wheel, near the pitch point of the gear drive, in rolling bearings etc. The portion of adhesive wear and scuffing increases at increase of the relative sliding and they frequently become dominant type of damage.

The researches were carried out in the field conditions on the electro-train ER2-631 with the use of the existent and developed by us ecological friction modifiers (which were fed respectively on the steering and tread surfaces) meant for steering and tread surfaces and their feeding devices. The noise was measured near the contact zone during the studies with the use of the noise meter (model SL 5868P, Fig. 8).

From the noise sensor installed near the wheel flange, the signal was transmitted with the help of noise meter to the PC where it was registered and processed.

a b c

Fig.8. a) Electro-train ER2- 631 with modified steering and tread surfaces and noise measuring devices installed near the wheel flange; b) Device for modification of the wheel steering surface; c) The noise sensor installed near the wheel flange.

In Fig. 9 are shown the results of the noise measurements of the modified and non-modified wheel rolling with velocity 60 km/h, from where is seen decrease of the noise level for the modified wheel.

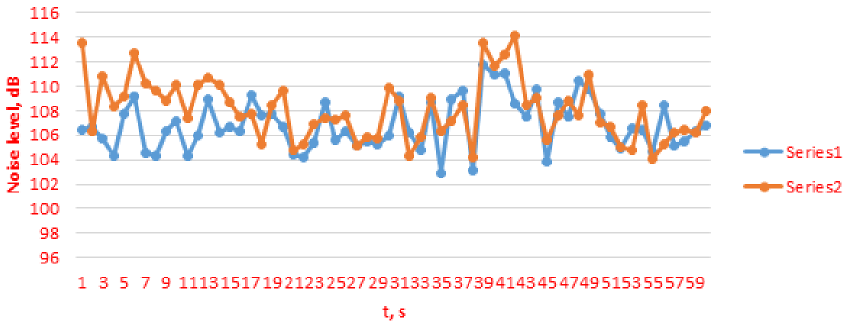

Figure 9. The results of the noise measurements of the modified and non-modified wheel: series 1 –modified wheel, series 2 – non-modified wheel.

At interaction of the wheel and rail, the noise level is stipulated by many factors, including the processes proceeding in the contact zone. As it is seen from Fig. 1 for modified wheel the noise level at its rolling on the rail, is decreased. Weakening of influence of the friction modifier at some places is explained by interference of external disturbing factors.

Conclusions

Velocity and safety of the railway traffic, energy consumed on traction, ecological compatibility and maintenance expenses greatly depend on tribological properties of the wheel and rail contact zone. The experimental researches carried out in laboratory conditions have shown dependence of the contact zone tribological properties on degree of destruction of the third body. For wheels and rails, destruction of the third body, direct interaction of juvenile parts of the surfaces lead to their seizure and scuffing, that stipulates the vibrations, noise and catastrophic wear.

Number of parameters influencing interaction of the wheel and rail rises in the field conditions that generates additional sources of noise having negative influence on precision of measurement of the contact zone noise.

Acknowledgment

Shota Rustaveli National Science Foundation of Georgia (SRNSFG) supported this work under GENIE project CARYS-19-588.

References

[1] K.C Ludema. FRICTION, WEAR, LUBRICATION. A TEXTBOOK IN TRIBOLOGY. 1996 CRC Press LLC. ISBN 0-8493-2685-0.Printed in the United States of America, 263 p.

[2] Railroad and Locomotive Technology Roadmap, Centre for Transportation Research Argonne National Laboratory, by Frank Stodolsky, Roadmap Coordinator, December 2002.

[3] Controlling of wheel squeal on rapid transit systems. IRJ, October, 2004, pp.30-31.

[4] Engineering Manual Track and Rolling Stock. TMC 213 Derailment 16 Transportation Systems Analysis and Assessment Investigation - Track and Rolling Stock. Version 1.0; August 2011.

[5] Engineering Manual Track andRolling Stock. TMC 213 Derailmentransportation Systems Analysis and AssessmentInvestigation - Track and Rolling Stock.Version 1.0; August 2011

[6] George Tumanishvili, Tengiz Nadiradze, Giorgi Tumanishvili. A new Concept of the Mechanism of Variation of Tribological Properties of the Machine elements Interacting Surfaces. pp. 131-150, In the book “Tribology in Materials and Manufacturing – Wear, Friction and Lubrication”. IntechOpen, Edited by Amar Patnaik, Tej Singh and Vikas Kurshal. London, 2021.

[7] Ulf Olofsson at all. Tribology of the wheel-rail contact – aspects of wear, particle emission and adhesion. Vehicle System Dynamics; Special Issue: State of Art Papers of the 23rd IAVSD in 2013. http://dx.doi.org/10.1080/00423114.2013.800215.

[8] U. Olofsson∗, T. Telliskivi. Wear, plastic deformation and friction of two railsteels—a full-scale test and a laboratory study. Wear 254 (2003) 80–93.

[9] Vidaud M., Zwanenburg W-J., Current situation on rolling contact fatigue – rail wear phenomenon. 9th Swiss transport research conference. Monte Verita / Ascona, September 9 – 11, 2009, pp. 1-27. Widaud http://www.strc.ch/conferences/2009/Vidaud.pdf.

[10] ASM Handbook, Friction, Lubrication and Wear Technology, 10th ed., Vol. 18, 1992. M. ISHIDA, M.AKAMA, K. KASHIWAYA and A. KAPOOR. The current status of theory and practice on rail integrity in Japanese railways-rolling contact fatigue and corrugations. 2003 Blackwell Publishing Ltd. Fatigue Fract Engng Mater Struct 26, 909–919.

[11] Kenneth C. Ludema. Review of Scuffing and Running in of Lubricated Surfaces, with Asperities and Oxides in Perspective. Wear, 100 (1984) 315 – 69 331.

[12] F. Braghin a, R. Lewis b, R.S. Dwyer-Joyce b, S. Bruni. A mathematical model to predict railway wheel profile evolution due to wear. Wear 261 (2006) 1253–1264.

[13] [31] Lewis R., Dwyer-Joyce R.S., Bruni S., Ekberg A., Cavalletti M., Bel Knani K.. A New CAE Procedure for Railway Wheel Tribological Design. 14th International Wheelset Congress, 17-21 October, Orlando, USA.

[14] Eadie DT, Kalousek J, Chiddik KC.The role of high positive friction (HPF)modifier in the control of short pitchcorrugations and related phenomena.Wear. 2002;253:185-192.

[15] Lewis R, Dwyer-Joyce RS. Wearmechanisms and transitions in railwaywheel steels. Proceedings of theinstitution of mechanical engineers, partJ. Journal of Engineering Tribology.2004;218(6):467-478.

[16] Tumanishvili G, Natriashvili T, Nadiradze T. Perfection of technical characteristics of the railway transport system Europe-Caucasus-Asia (TRACECA) in the book. In: Sladkowski A, editor. Transport Systems and Delivery of Cargo on East-West Routes, Springer. 2018. pp. 303-368.

[17] Curt A. Swenson. Locomotive Radial Steering Bogie Experience in Heavy Haul Service. IHHA'99. 1999, pp. 79-86.

[18] C. Yang, F. Li, Y. Huang, K. Wang, B. He. Comparative study on wheel-rail dynamic interactions of side-frame cross-bracing bogie and sub-frame radial bogie. J. Mod. Transport. 21(1) c1-8. DOI 10.1007/s40534-013-0001-3.

[19] D.T. Eadie, M. Santoro & W. Powell: Local control of noise and vibration with KELTRACK™ friction modifier and Protector® trackside application: an integrated solution, Journal of Sound and Vibration, Vol. 267, Issue 3, October 23, 2003, pp. 761-772.

[20] Christophe Collette, Mihaita Horodinca and Andre Premont. Rotational vibration absorber for the mitigation of rail rutting corrugation. Vehicle System Dynamics Vol. 00, No. 0, Month 2008, 1–19.

[21] George TUMANISHVILI, Tamaz NATRIASHVILI, Tengiz NADIRADZE, Giorgi TUMANISHVILI. Estimation of Parameters of the Rail Corrugation. International Journal Of Advancement In Engineering Technology, Management and Applied Science (IJAETMAS). ISSN: 2349-3224, www.ijaetmas.com. Volume 04 - Issue 09, September-2017. PP. 94-102.