ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1217194

INNOVATIVE UNIVERSAL VEHICLE FOR EXPERIMENTAL TESTS ON ROLL-OVER STABILITY OF OFF-ROAD WHEELED MACHINES AND VEHICLES

Piotr Dudziński, Gustaw Sierzputowski

Wroclaw University of Technology
Department of Off-Road Machine and Vehicle Engineering
Łukasiewicza Street 7/9, 50-371 Wroclaw, Poland
tel.: +48 71 3215396, +48 71 3202718
e-mail: piotr.dudzinski@pwr.edu.pl, gustaw.sierzputowski@pwr.edu.pl

Abstract

The current standards in roll-over stability of off-road wheeled machines and vehicles do not include many significant factors of their design and performance (e.g. suspension type and parameters, stiffness of tires) as well as operation conditions (e.g. inclination and bearing capacity of the ground). In practice, it results in many dangerous roll-over accidents, particularly of articulated body steer vehicles, which might involve the operator's death and/or severe damage to the machine and its surroundings. In recent years, some solutions developed and applied by particular companies aimed at roll-over stability improvement have been noticed. Unfortunately, their use appears to be not optimal and the aggregated knowledge remains usually a know-how of the company. For comprehensive explanation of this problem the Division of Off-Road Machine and Vehicle Engineering has built the innovative universal test vehicle for experimental tests on roll-over stability of off-road wheeled machines and vehicles. This unique at global level, universal test vehicle enables the undercarriage structure and properties to be optionally selected and roll-over stability to be tested on special rotary-tilting platform with on-line measurement of three components of reaction forces under each wheel. The paper presents the parameters and research potential of the original universal tests vehicle with the exemplary tests results.

Keywords: *off-road machines and vehicles, roll-over stability, innovative universal wheeled test vehicle*

1. Introduction

The roll-over stability is one of the most important operating characteristics in the off–road machines and vehicles. Unfortunately, as a rule, the requirements concerning maintaining the desired stability are in conflict with the requirements concerning the expected high mobility and manoeuvrability or the construction of the working machine. For example, the large stroke of suspension helps tilt the vehicle increasing the risk of roll-over. Moreover, because of the high clearance and movable boom, the reduced centre of gravity of a vehicle is located at relatively high altitude and its position is variable. Particular difficulties related to assuring high roll-over stability appear in the articulated body machines and vehicles which, due to their high operating manoeuvrability are now widely used [2]. The disadvantage results primarily from the fact that for that class of machines and vehicles the reduced centre of gravity during turn relocates in direction of the potential roll-over line lowering the stability reserve.

In the current European standard ISO 14397-1:2007 [1] (or its Polish equivalent PN-EN474-3+A1:2009), concerning totally the safety of machines for earth works, some criteria for evaluation of the roll-over stability for that class of vehicles have been defined. However, the criteria do not warrant the sufficient roll-over stability of the working machine in typical condition of its operation. As an example, in case of the wheeled articulated bucket loader, the cited standard involves the guidelines concerning the roll-over stability exclusively in the context of the maximum bucket load. In consideration, there is only one tipping line (Fig. 1) – that passing through the contact surface of the front wheels axis with the base. The standard indicates that for the nominal load Q_N of the loader bucket, in the quasi-static conditions and at the maximum reach of the arm and the maximum turn of the machine members, the load of the bucket with load lower than $2Q_N$ should not lead to the lifting of a single rear axle wheel.

In no way, the standard relates to the roll-over stability in other directions (around the remaining tipping lines). Also, the impact of the sloping ground ($\alpha_{CRIT} = 0$), stiffness of tires and the ground, as well as the dynamic reaction forces resulting from the machine movement over the ground of the stochastic character of inequalities has also been omitted. Further, the effective standard does not take into account such vital constructional parameters as: undercarriage steering system (the articulated vehicle, the steering wheels vehicle etc.), localisation and possible tilt angles of steering joints and/or the deflection, as well as the suspension type (dependent, independent etc.) of the wheels or bridges. An example would be the vehicle equipped with oscillating driving axle. The important function of such dependent suspension is providing in the quasi-static conditions, within the range of variation of the oscillation angle (usually about ±12°), the high mobility of the vehicle – manifesting among others in permanent contact of all four wheels with uneven ground. However, in case of the flat ground the roll-over stability of a vehicle decreases. The „quadrangle of stability" present with the rigid suspension (Fig. 1b-c), is replaced by three potential tipping axes (Fig. 1d) creating the „triangle of stability" [9].

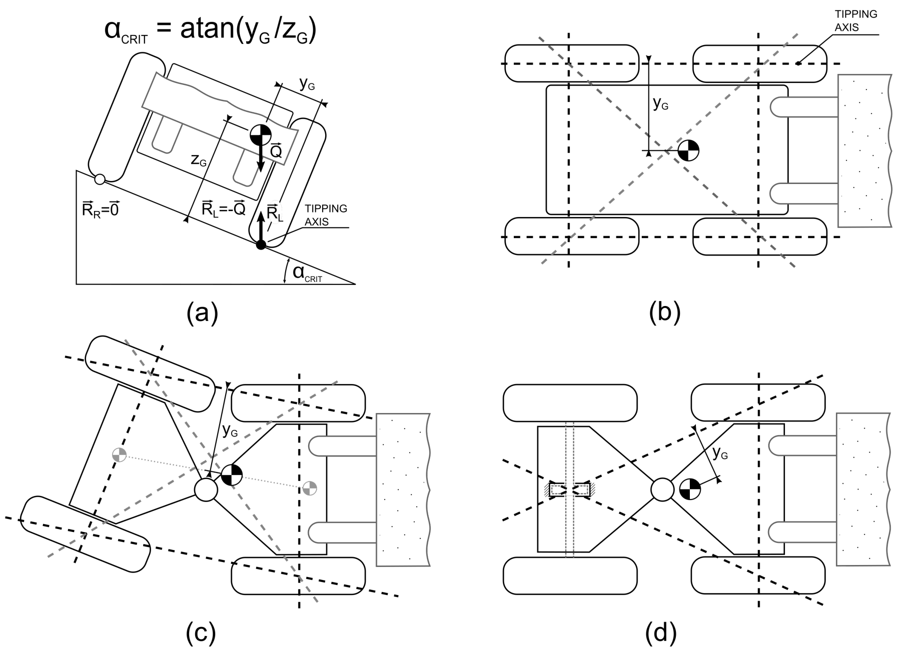


Fig. 1. Tipping axes: a – the method of determining the critical ground inclination angle, b – tipping axes in the vehicle with a rigid frame, c – dislocation of the gravity centre at the twisted articulation, d – tipping axes in the vehicle with the self-aligning bridge

A series of the many-years theoretical and experimental research performed at the Department of Off-Road Machine and Vehicle Engineering of Wroclaw University of Technology, shows strong relation with roll-over stability of both, the type and parameters of the suspension system applied in the vehicle (Fig. 2), as well as the stiffness of tires and ground themselves [1, 3-6, 8, 11, 12].

The confirmation for the necessity of discussion of the effective standards related to the roll-over stability of off-road machines and vehicles are also, unfortunately, very frequent accidents related to the loss of the roll-over stability – often combined with serious injuries and even death of the operator or the persons staying in the vicinity of the machine (Fig. 2). The research performed in the town of rural region of Turkey, Kardamon [10], show that for 601 of all the recorded there cases of death within 2004-2009, as much as 42 of them (6.98%) was caused by roll-over of the agricultural vehicle.

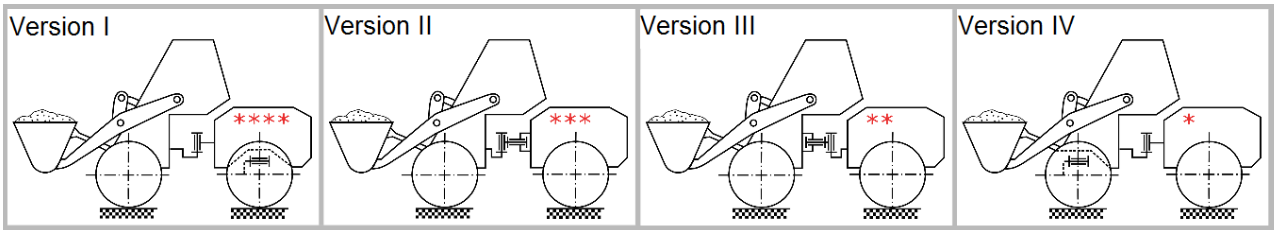


Fig. 2. The impact of the oscillation joint localisation with horizontal axis on roll-over stability of the articulated wheel bucket loader (greater number of stars indicates for higher roll-over stability) [4]

Producers of off-road machines and vehicles are conscious of the impact of the structure and properties of the chassis system on the roll-over stability. To improve this important operation indicator, there are continuously developed numerous non-conventional suspension systems [7] – increasing the machine stability without lowering the required mobility. An example of this may be the inclined oscillation axis located between the front and rear bodies of a vehicle (Fig. 3), [8], [13]. However, there is lack of complex, generally available knowledge on the influence of those solutions and their parameters on the roll-over stability of a vehicle.

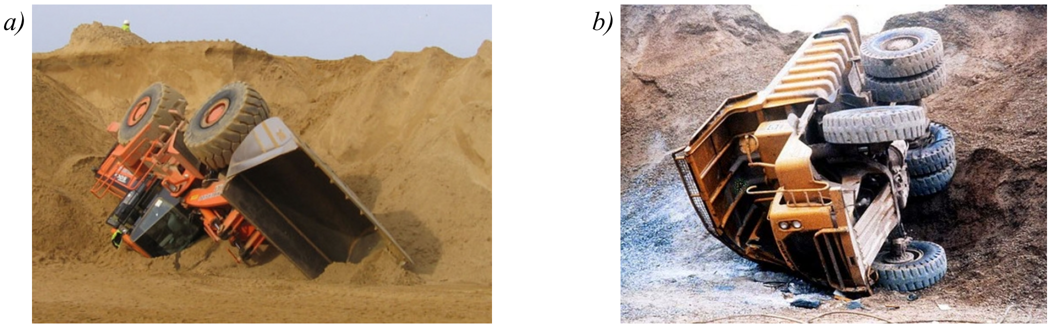


Fig. 3. Examples of losing the roll-over stability in the machine for ground works during their operation: a – articulated bucket loader [14], b – dump with the so called rigid frame [15]

The popular criterion of losing stability based at tipping edges concerns the static stability excessively simplifies the phenomenon and does not allow evaluation of impact of the suspension mechanisms of modern vehicles of spatial character on the roll-over stability. Thus, the Authors propose the direct analysis of normal reaction forces between wheels of a vehicle and ground and applying, depending on the needs, one of the two types of stability loss, in accordance with [11]:

(Def. 1) Loss of the roll-over stability of the I type takes place in case of appearance of zero normal reaction force between one of the vehicle wheels and ground.

(Def. 2) Loss of the roll-over stability of the II type takes place in case of appearance of zero normal reaction force between two of the vehicle wheels and ground.

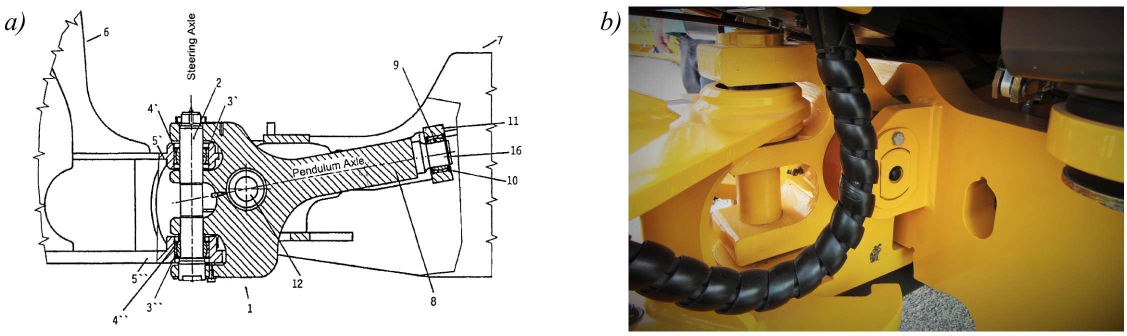


Fig. 4. An exemplary solution of articulation joint and the inclined axis' oscillation joint between bodies of a vehicle applied by Volvo; a – illustration from the patent [13], b – an example of application (own data)

2. Innovative universal wheeled test vehicle

In response to the urgent industrial need, Department of Off-Road Machine and Vehicle Engineering at the Wroclaw University of Technology has developed and produced the universal wheeled test vehicle for tests of the roll-over stability (Fig. 5, 6a). The stand for tests of the roll-over stability consists of the universal test vehicle standing at the rotary-tilting platform. Under each of the vehicle wheels the sensing plates developed by the Department are located enabling measurement and acquisition of all three components of reaction force. The orientation of the platform in relation to the gravity vector is determined based at readings of the bi-axial inclinometer. For the data acquisition, the multichannel industrial computer from National Instruments is used. The turn and tilt of the platform are controlled by typical hydraulic station.

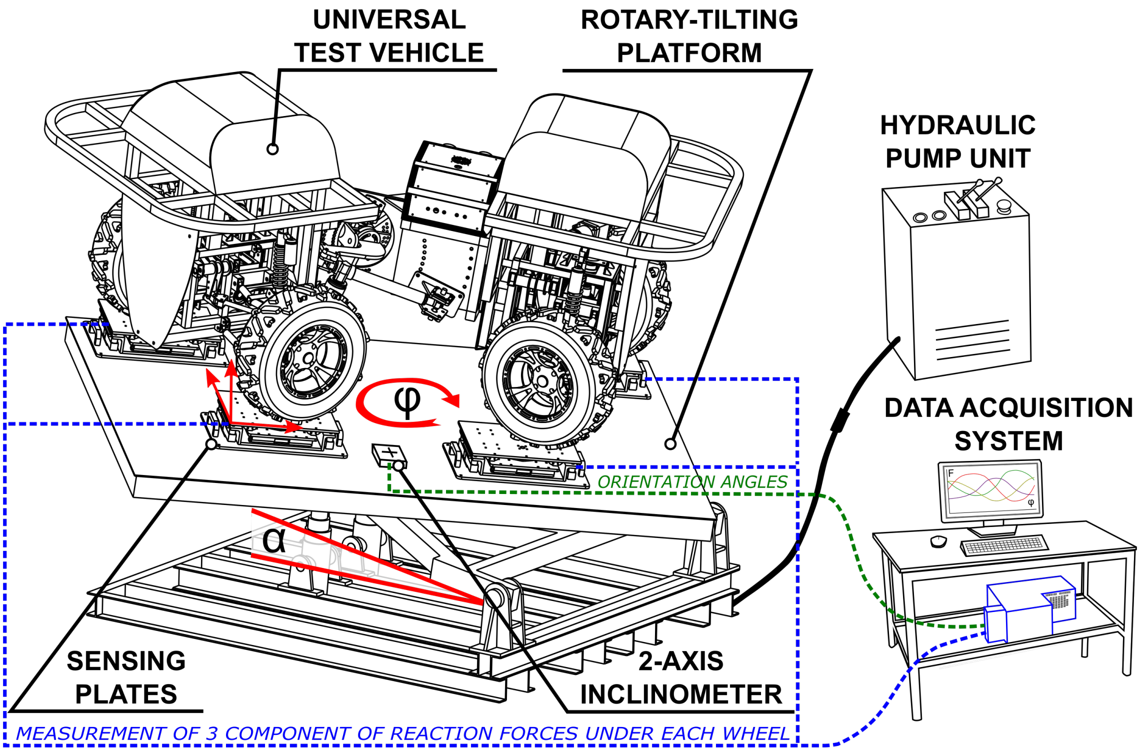
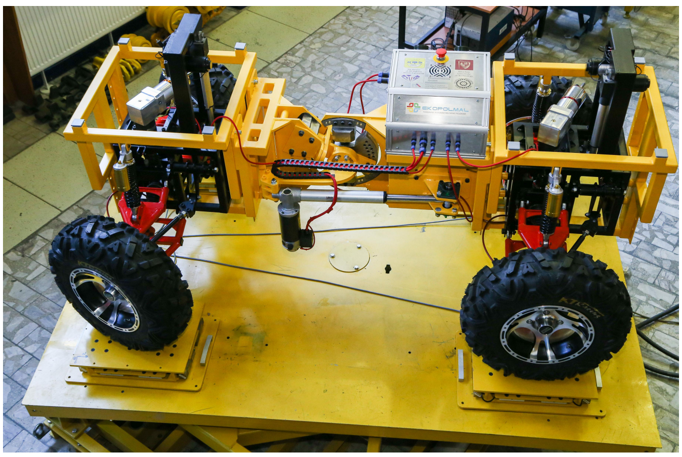


Fig. 5. Schematic of the stand developed for tests of the roll-over stability of wheeled vehicles of arbitrary structure and properties of the undercarriage system

a)



b)

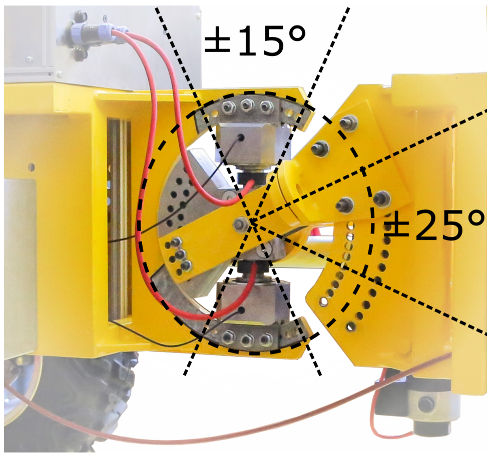


Fig. 6. The innovative universal test vehicle of adaptable structure and properties of the undercarriage system at the tilting-rotary platform equipped with 3-axial measurement plates

Due to the in-depth study of the current state of knowledge and techniques, as well as reaching for the modern technical solutions, the created innovative universal test vehicle has been the unique unit worldwide in terms of the range of structure variants and variability of the simulated parameters of the undercarriage systems. It has to be added here that the research potential of the fully functional wheeled vehicle significantly exceeds the currently discussed studies of the static and dynamic roll-over stability. Application of the modular build and the thoughtful design of individual vehicle bodies enabled interference both, in type and parameters of the chassis, drive and brake systems – such as:

- the articulation joint of the work range from –43° to 38°,
- variable inclination angle of the articulation joint within the range of ±15° (Fig. 6b),
- the articulation joint with built-in system enabling measurement of all forces and moments acting on it (Fig. 6b),
- the steering wheels within the range of about ±50°, controlled independently,
- variable wheelbase and the location of the steering joint position in relation to axis (Fig. 7),
- available different suspension types:
  - rigid, with elasticity only in tires,
  - independent double wishbone suspension with controlled elastic-dumping characteristic,
  - dependent in the form of oscillating driving axle with variable altitude of oscillation axis and with the variant of additional elastic-dumping components,
  - dependent in the form of oscillating body with variable altitude of oscillation axis,
- adjustable inclination angle of the oscillation joint axis located between the front and rear part of the vehicle, within the range of ±25° (Fig. 6b),
- the 4WD (4x4) or 2WD (2x4) drive at the front or rear axle,
- each axle equipped with selectable locking differential mechanism,
- each half-axle equipped with mechanical clutch,
- the possibility of introducing the electronic centre differential mechanism,
- each of the wheels equipped with hydraulic disk brake, break system of the fast reaction and possibility of independent braking for individual wheels,
- the possibility of a smooth change in mass parameters of a vehicle by assembling additional weights and the external loading frames.

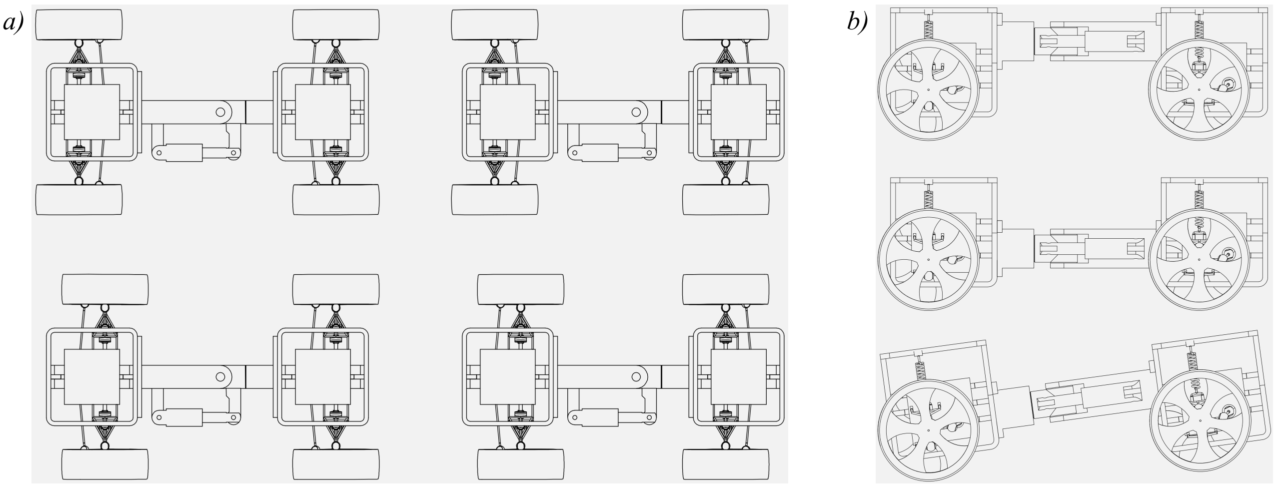


Fig. 7. Special construction of the developed universal test vehicle enables changes in many geometrical parameters of the undercarriage system such as: a – wheelbase and the position of the articulation joint, b – height and location of the crossing point of the articulation joint axis with oscillation joint axis.

3. Summary

The presented above innovative universal test vehicle has been created within the doctoral thesis which is being developed in the Department of Off-Road Machine and Vehicle Engineering at the Wroclaw University of Technology. Its structural design constitutes a part of the research project being implemented by one of the Co-authors within the frames of the „Diamond Grant" program. Within that project also the mathematical model for determining the roll-over stability of wheeled vehicles of arbitrary structure of the undercarriage system is being developed. The empirical verification of the theoretical model will be performed at the presented innovative test vehicle.

Acknowledgment

The article was funded from the public budget by the Polish Ministry of Science and Higher Education as the "Diamond Grant" research project, part of the 2013-2016 Education Programme resources.

References

[1] Dudziński, P., Kosiara, A., *Wpływ podatności opon oraz podłoża na stateczność wywrotną przegubowej maszyny roboczej na podwoziu kołowym*, Transport Przemysłowy i Maszyny Robocze, No. 2(28), Wroclaw 2015.
[2] Dudziński, P., *Leksysteme für Nutzfahrzeuge*, Springer−Verlag, Berlin Heidelberg 2005.
[3] Dudziński, P., Pieczonka, K., *Sposób i układ do sygnalizowania utraty stateczności maszyny na podwoziu kołowym, w szczególności ładowarki lub koparki*, Patent nr 163932.
[4] Dudziński, P., Pieczonka, K., *Układ do kontroli udźwigu i pomiaru rzeczywistej wydajności ładowarek łyżkowych na podwoziu kołowym*, Patent 159730.
[5] Dudziński, P., Pieczonka, K., Wysłuch, Z., *Automatic systems for steering and controlling bucket loaders: searching for solutions*, Proceedings of the 1st International Conference Off-Road Machines in Theory and Practice, Wroclaw 1996.
[6] Dudziński, P., *Problems of dynamic rollover stability on wheeled off-highway vehicles*, Proc. of 13th International Conference of the ISTVS, Munich, Germany 1999.
[7] Dudziński, P., Sierzputowski, G., *Przegląd układów podwoziowych kołowych pojazdów przemysłowych w świetle istotnych wskaźników eksploatacyjnych*, artykuł w opracowaniu.
[8] Dudziński, P., Siwulski, T., *Wpływ ukształtowania przegubowego zespołu jezdnego na stateczność wywrotną kołowej maszyny roboczej*, Transport Przemysłowy i Maszyny Robocze, No. 4 (26), Wrocław 2006.
[9] Gibson, H. G., Elliot, K. C., Persson, S. P. E., *Side slope stability of articulated-frame logging tractors*, Journal of Terramechanics, Vol. 8, No. 2, pp. 65-79, 1971.
[10] Özdeş, T., Berber, G., Celik, S., *Death cases related to tractor overturns*, Turkiye Klinikleri Journal of Medical Sciences, Vol. 31, 1, pp. 133, 2011.
[11] Pieczonka, K., *Analityczne metody wyznaczania podstawowych wielkości konstrukcyjnych i eksploatacyjnych samojezdnych maszyn przegubowych*, Prace Naukowe Instytutu Konstrukcji i Eksploatacji Maszyn Politechniki Wrocławskiej, No. 31, 1976.
[12] Pieczonka, K., *Inżynieria maszyn roboczych: Podstawy urabiania, jazdy, podnoszenia i obrotu. Część 1*, Oficyna Wydawnicza Politechniki Wrocławskiej, 2007.
[13] Seebohm, W., Kohn, P., Inventors, Volvo Compact Equipment Gmbh and Co, assignee, *Articulated pendulum steering system*, US patent 6.932.373, 23.08.2005.
[14] www.hse.gov.uk.
[15] www.miningmayhem.com.