Providing vehicle running life in case of loss of tyre air pressure

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Abstract. This paper comprises general information on the tyre air pressure loss problem and methods for ensuring vehicle mobility in case of such pressure loss, namely the information on current tyre-wheel system development trend, as well as the use of special internal supports (run-flat) of different design. Furthermore, the paper describes practical aspects of implementation of this system, reveals positive and negative characteristics and contains a conclusion on the system development prospects depending on their application.

1. Providing vehicle running life in case of loss of tyre air pressure

The problem of ensuring traffic (vehicle motion) safety in case of sudden tyre damage leading to complete loss of air pressure is always relevant.

Loss of internal pressure leads to deformation, bead come-off from the wheel bead ledge and tyre destruction. It impairs vehicle stability and leads to an accident in most cases. The research by Dunlop (England) shows that, on the European roads, tyre failures due to mechanical damages amount to 40%. According to the estimation by the Federal Statistical Office (Germany), there are more than 1,500 accidents a year happening because of the tyre defects in Germany. The striving to improve traffic (motion) safety in case of loss of tyre pressure led to the emergence of new tyre and wheel design variants.

Creation of tubeless tyres in 1954-1958 was a major step in this direction. In case of foreign item penetration, tubeless tyres are less prone to a sudden drop in pressure, however, after the damage, the tyre running life reduces, though it is still longer than the one of a tube tyre. This problem is partially solved by application of a rubber-cord spacing ring.

However, it does not solve the safety problem completely. Moreover, a need appeared to create special tyres and systems named "safe" for general-purpose vehicles, and for special vehicles, mainly for the Ministry of Defence and security services – "bullet-proof". The purpose of such structures is ensuring sufficient sealing of the hole in case of a puncture and stable vehicle motion. In order to provide the possibility to drive a vehicle with a flat tyre, the safe tyres shall be highly resistant to side slip allowing vehicle control without drifting on a straight road caused by lateral forces and when turning, as well as when performing road maneuvers, tyres shall keep their position on the rims so that the beads are not displaced and shall not come off from the wheel bead ledge.

The safety improvement problem also includes creating safe tyre-wheel systems and other methods of increasing tyre functionality in case of operational damages. The major tyre and automotive companies of
Europe, USA, Japan, and other countries work on creating designs of tyres and tyre-wheel systems ensuring vehicle motion safety in case of mechanical damage of the tyres.

All methods of increasing the tyre penetration resistance and bulletproof capability and ensuring reliable driving of a vehicle with a damaged tyre can be conditionally divided into two main groups: self-sealing of mechanical punctures on the tyre tread and ensuring long-term driving of a vehicle with a damaged tyre.

Traditional tubeless tyres including various sealing compositions and tyres with special spongy layers in the internal cavity under the tyre tread belong to the first group. The sealing liquids are characterized by the following properties: prevention of air leakage, keeping nominal operating pressure in tyres and reduction of tyre heating. Being inside the tyre during the whole service life, such liquids remedy punctures when these emerge. They do not cause tyre disbalance, steel rusting, disc corrosion or rubber destruction. The sealing liquids maintain their operational properties in a wide range of temperatures (from -20 to +75 °C). Thus, the use of sealing liquids in tyres is of interest in terms of vehicle motion safety.

One of the tyre design options allowing further driving after the tyre damage is a highly self-sealing tyre such as Seal Inside by Pirelli (Italy), Figure 1. The internal surface of the basic innerliner is provided with an additional layer intended for self-sealing in case of small holes. This technology is effective for the majority of punctures, except for the punctures breaking the tyre integrity.

![Figure 1. Seal Inside tyre by Pirelli.](image)

For ensuring long-term vehicle motion with a damaged tyre or with all tyres damaged, new requirements shall be added to the abovementioned characteristics. Regarding the safe operation, it is important to ensure safety concerning tyre rupture or wheel failure and to have a reliable contact between the tyre beads and the rim edges; the tyre shall be also of tubeless type. With no air pressure in the tyre, the vehicle shall move without tyre destruction for up to 200 km at no less than 80 km/h, and, in case of 100% tyre damage, special vehicles shall remain mobile and run for up to 50 km at up to 50 km/h with a possibility of subsequent repair of tyres and wheels (and upon that, the through-hole size shall be no more than 8 mm, and the number of such punctures shall be no more than 10). It is also important to have reliable brake and tractive force transmission, to provide sustainable vehicle driving on dry, wet, ice- and snow-covered roads, to have low heat generation, and to sufficiently resist tyre side damages and feature low sensitivity to obstacle crossing.

Additional requirements for such tyres are as follows: low production cost, long service life and running life, recoverability and low rolling resistance. High comfortableness can be ensured by appropriate elasticity and absorption characteristics, optimum cornering resistance, as well as minimum lateral and radial runout.

Rigid wheel supports can be rotatable and non-rotatable. A wheel with rotatable rigid support consists, for example, of a tubeless tyre and sectors separately inserted into the tyre and bolted to each other. The rim is sealed by a ring rubber cord located in a cavity between the rim halves. A spacing ring holds the tyre bead on the bead ledges in case of the tyre air pressure drop. When the pressure drops, the tyre internal surface is set on the support, which reduces tyre radial deflection and bears most of the wheel load. In order to reduce friction between the tyre internal surface and the support, the latter can rotate about the rim on a friction
(slide) bearing over the spacing ring external surface.

The two-segment internal additional support (IAS) design (Rodgard, Figure 2) by Hutchinson considerably simplifies installation of the support within the tyre. The Rodgard design also features a pilot (guide) friction bearing mounted on the rim, which the support can rotate about. According to the manufacturer, the structure can be mounted on a standard rim and ensure the run for up to 50 km with a flat tyre at no less than 50 km/h. As a rule, the number of segments is defined by the feasibility of in-tyre assembly.

![Figure 2. Rodgard IAS by Hutchinson.](image1)

NIIShP (Scientific Research Institute of the Tyre Industry) tested a wheel with IAS of the same design on the asphalted roads and on the soil tank road at 20-40 km/h. After 30 minutes of driving at 40 km/h, the tyre temperature reached 180 ºC. With the completely destructed tyre, the wheel with rotatable support did not provide torque transmission and vehicle mobility.

CRF IAS (Figure 3) by Hutchinson is assembled of three segments. According to the producer’s declaration, besides the relative simplicity of manufacturing and installation, it is distinguished by the strong bullet and splinter protection as a whole of the wheel center and tubeless tyre.

CRF provides run for up to 80 km maintaining vehicle drivability without air pressure in the tyres. IAS includes composite materials and is assembled by means of bolt joints.

![Figure 3. CRF IAS by Hutchinson.](image2)
In the assembled internal support connecting (detaching) points, there are connecting design elements, which are the stress raisers. Such stress raisers significantly increase the probability of the structure failure in case of the exposure to bending moments arising during the vehicle turning. Besides, the wheel running gear vibration loads connected with the drop of the vehicle longitudinal stability when driving with flat tyres significantly increase. Failure of the great majority of detachable IAS under test happens because of destructions in the support connecting points.

An illustrative example of the rigid insert is the metal support ring – Continental Support Ring (CSR) IAS (Figure 4) by Continental – which is mounted along with a standard tyre on a regular rim. During normal driving, the CSR insert does not influence the vehicle's operational properties. In case of tyre pressure loss, further vehicle motion is possible with the top speed of 80 km/h for up to 200 km. CSR is generally offered for equipping AWD passenger cars.

The design can be used on the majority of standard rims in combination with many tyre types. After long and comprehensive testing, Maybach and Bentley decided to use this system to increase their vehicles' safety. Similar designs became widespread and are patented by many foreign companies, including Yokohama.

The safe tyre design was considerably simplified by supports made either of rubber only or of combined (rubber and metal) material that increases the stiffness and acting as spacing rings for fixing beads and supports.

The design manufactured since 2002 by Michelin – PAX System (Figure 5) – has become the most widespread one. It was installed on Audi A8, Rolls-Royce Phantom, Audi A4 and Honda Odyssey passenger cars.

In case of tyre pressure loss, an elastic insert helps the tyre sides to keep their shape – it is a ring mounted inside and fixed on the rim.

According to the manufacturer, a vehicle equipped with the PAX system can run no less than 200 kilometers at up to 80 km/h with a flat tyre. Any external force impact on the wheel increases the stress inside the tyre, the beads of which represent a locking gear (beadlock) and can transmit the torque from the rim even if there is no tyre overpressure. In the tyre attachment points, the cord is clamped in the slot, so that the tyre is locked on the rim and cannot come off from the wheel bead ledge even under high dynamic loads. For reducing friction between the support and the tyre, the tyre internal surface is covered with a special greasing layer. At present, tyres with the PAX system are actively used on armoured executive vehicles, as well as on some passenger car models.
In many design versions, the torque is transmitted from the rim to the tyre by means of pressing its beads to the rim edges. In this regard, a need emerged to eliminate friction in the IAS tread contact with the tyre.

Non-detachable VFI IAS for heavy armoured wheeled vehicles are produced by Hutchinson (Figure 6). Despite the need to use a special device pressing the support rubber ring to put it inside the tyre, there is a tendency for such support design application. Due to the absence of connecting elements, the design mass and number of stress raisers in the elastic ring are reduced. According to the manufacturer's declaration, the design provides the run with a flat tyre for up to 50 km at no less than 50 km/h.

A Russian IAS example is the petal-type support offered by the 3rd Central Research Institute (CRI) of the Ministry of Defence of the Russian Federation (Figure 7) allowing reduction of destruction intensity of the tyre internal cavity in its contact with the support when rolling without overpressure due to reduction of slipping of the bending support petals. Furthermore, the design has also other advantages, such as easy support installation in the tyre due to its lower deformation (folding) resistance and better off-road performance on deformable soils with no air pressure in the tyre due to lower radial stiffness of the support. It should be noted that the internal support stiffness reduction results in bigger internal friction losses which leads to the increase of the wheel rolling resistance and to higher thermal load on the structure.
A special group of tyres designed to ensure running in case of partial and full internal pressure loss comprise the tyres with high own stiffness or with a special tyre side structure. In the Continental concern, such tyre was named SSR, in Michelin – SST, and in Bridgestone – RFT. The cornerstone of the technology is a rather simple postulate: in order to continue moving with a zero-pressure tyre, its sides shall withstand all dynamic and static loads, which are borne by the tyre in the inflated condition. Despite the simplicity of the idea, its implementation took quite a long time and even demanded to join efforts by several tyre concerns to create a special material that could be applied for the run-flat tyre sides (Figure 8). According to the producer's declaration, the technology allows the vehicle to move for no less than 80 km more at up to 80 km/h.

All run-flat tyres require obligatory use of the tyre pressure monitoring system. Using the tyres on vehicles, which are not regularly equipped with such system, is inadmissible. Upon that, the run-flat tyres do not demand application of any special rims. Nevertheless, their installation requires special tyre mounting equipment due to the higher tyre side stiffness.
Disadvantages of such tyres are as follows:
1) if a tyre puncture is not noticed in due time, it may cause unexpected effects in an emergency situation;
2) higher vibration and worse steerability on rough roads;
3) these tyres are barely subject to repair;
4) bigger rubber weight that causes increased non-sprung weight, worse steerability and dynamic characteristics.

A safe wheel with a carcass-type tyre without internal overpressure represents a new tyre design direction. The tyre can operate without internal pressure as a result of replacing the carcass threads under tension by elastic sprung wires bearing the tyre radial load. Abroad, great attention is paid to this direction and research activities are conducted very intensively, especially in the Michelin research center. The wheel with the atmospheric pressure tyre was named Tweel. For the first time, the Tweel system (Figure 9, a) was used in traditional wheelchairs where tyre inflating is the number one problem. Then, an improved tyre was tested on Audi A4. In this tyre, the rubber tread is supported by flexible polyurethane spokes. Its testing continues.

At present, Michelin intends to enter the market with the Tweel system (Figure 9, b) for applications with low speed and low weight. Certain progress in creating tyres operating at the atmospheric pressure was reached also in Russia. Originally, the idea of a carcass tyre was implemented on a 3.5-10 tyre. Upon that, the selected safe carcass tyre has shown the values of side and radial stiffness, as well as of uniformity, rolling resistance at the level of similar pneumatic tyre values. When testing in NIIShP, the tyre was damaged by drilling through-holes with a diameter of 12.5 mm (2 on the tyre side and 2 on the tyre tread). According to the bench tests, the drilled holes have no impact on the characteristics of the tyres and their running life on the test bench.
Figure 9. Tweel tyres by Michelin. First concept of 2005 (a) and later models (b).

The following development by Michelin is slightly more original – a tyre named Airless (Figure 10) made from elastic rings with pre-determined longitudinal, transverse and vertical stiffness.
The abovementioned rings are made of a patented mix including thermosetting resin, fiberglass and polyurethane. The advantage of the French development is that strong impacts and sharp objects damage only separate tyre elements, therefore, the wheel is distinguished by the highest survivability.

A little later, the American company Amerityre offered a design similar to the Michelin Tweel: composite wheel where the rubber tyre tread is connected to the rim through flexible polyurethane spokes (Figure 11).

The creators declare lower operating temperature (that means low tyre tread wear) and lower rolling resistance (that means low fuel consumption). The short-term outlook for such wheels is mass production.
and delivery to conveyors as space-saving tyres (donuts). Similar tyre designs were developed by Japanese Bridgestone with AirFree concept (Figure 12, a) and American Hankook with its I-Flex (Figure 12, b).

![AirFree by Bridgestone (a) and I-Flex by Hankook (b).](image)

The Hankook engineers state that the I-Flex technology developed by them allows wheels to operate at up to 130 km/h, and upon that such tyres can be installed on standard rims. A demonstration of the company possibilities was the tyres for Volkswagen Up! city car in the ABT version presented in 2013.

At the moment, different airless tyre variations are not ready to conquer the automobile market, as they perfectly proved themselves on off-road and special vehicles. At the same time, bringing rolling resistance to modern standards, lowering noisiness and improving long-drive heat resistance of the airless tyres can make them peer competitors of traditional tubeless tyres.

**Conclusion**

Thus, analysis of a number of safe and bullet-proof wheel designs allows determining certain trends in evolution of a structural form of the solutions applied on vehicles including special and military wheeled vehicles.

1. At present, the most promising design of the safe wheels for general-purpose vehicles are carcass-type tyres without internal overpressure.
2. For special and military vehicles, the advantages of safe and bullet-proof wheels with IAS are obvious.
3. In modern designs, thermoplastic polymers or elastomers, mainly polyurethanes, are used as IAS material. These materials have such properties as durability, lightness and elasticity. Damages, high temperatures and dynamic loads have no significant effect on the functionality of the supports made of these materials.
4. The most promising IAS designs are designs compatible with standard wheel rims.
5. The majority of IAS installed on foreign special-purpose vehicles weighing up to 6-7 t are assembled in a tyre of two or three identical segments. This is explained by relative simplicity of design installation in a tyre and a small number of parts.
6. When selecting the IAS segment connecting method, reduction of stress concentration in the connecting points shall be taken into account.
7. The problem of high friction between IAS and the tyre is not finally solved at the moment, in spite of the fact that friction in the IAS-tyre contact is one of the main factors leading to the tyre destruction.
Measures to reduce friction between design elements, for example, greasing with high viscosity coefficient, will allow inhibiting tyre tread deterioration and increasing the vehicle run after the tyre damage.

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