**Bogusław CIEŚLIKOWSKI**
Uniwersytet Rolniczy im. Hugona Kołłątaja w Krakowie, Wydział Inżynierii Produkcji i Energetyki, KIMiA
ul. Balicka 120, 31-149 Kraków, Poland
e-mail: cibogdan@poczta.onet.pl
**Mariusz CYGNAR, Anna KOCHANEK**
Państwowa Wyższa Szkoła Zawodowa w Nowym Sączu, Instytut Techniczny
ul. Zamenhofa 1a, 33-300 Nowy Sącz, Poland
e-mail: krz_jur@wp.pl

# MODIFICATION OF THE PROCEDURE OF DIAGNOSTIC INFERENCE FOR TPMS

*Summary*

*The subject of the paper is to modify the procedure of inference for TPMS (Tyre-Pressure Monitoring System) with regard to an earlier identification of the excessive temperature rise in tyres before they exceed thermal limits. This shall allow to limit the risk of accidents caused by destruction of a tyre. An important issue indicating functional features of TPMS consists in a possibility of rapidly warning a driver immediately after a potentially dangerous rise of temperature. Traction tests have been carried out with use of a passenger car equipped with TPMS with P409 sensors and TH9P409S measuring module. Time characteristics of tyre temperature signals were included indicating the way of their use for the process of estimation of a warning signal. A change trend model of an analysed parameter in time function was developed.*
**Key words**: *TPMS, tyre temperature control*

# MODYFIKACJA PROCEDURY WNIOSKOWANIA DIAGNOSTYCZNEGO DLA UKŁADU TPMS

*Streszczenie*

*Przedmiotem publikacji jest modyfikacja procesu wnioskowania w systemie TPMS (Tyre Pressure Monitoring System) w zakresie wcześniejszej identyfikacji nadmiernego przyrostu temperatury opony zanim zostaną przekroczone limity dopuszczalne. Pozwoli to na ograniczenie skutków destrukcji opony zmniejszając przy tym ryzyko wypadkowości. Istotnym zagadnieniem wyrażającym cechy funkcjonalne układu TPMS jest zdolność szybkiej estymacji sygnału ostrzegawczego o stanie awaryjnym opony. Przeprowadzono testy trakcyjne samochodu osobowego wyposażonego w układ TPMS z czujnikami P409 i modułem pomiarowym TH9P409S. Zamieszczono charakterystyki czasowe sygnałów temperatury opony wskazując na ich wykorzystanie dla estymacji sygnału ostrzegawczego. Opracowano model trendu zmiany analizowanego parametru w funkcji czasowej.*
**Słowa kluczowe**: *TPMS, kontrola temperatury opony*

## 1. Introduction

Vehicles are currently equipped with a tyre-pressure monitoring system (TPMS) designed to monitor the air pressure inside the pneumatic tires informing a driver about changes in pressure and temperature inside a tyre as a result of a mechanical damage, exceeding the nominal load or an incorrect initial pressure. According to the new EU directive adopted in March 2009, all new vehicles sold within the borders of the European Union must be equipped with this control system. The directive came into force as of 11th January 2012. However, the deadline to comply with the directive was established for 1st November 2014. Thus, after this date, all new approved vehicles must be equipped with the tyre pressure control system (called RDKS/TPMS).

The EU 2010 Initiative "The Intelligent Car" initiated within the European Commission was the genesis of these activities. Besides this Institution undertakes a wide range of innovative technologies in the automotive industry. The importance of the pressure monitoring system in twin wheels was especially highlighted since a reduction in pressure in one of the wheels leads to exceeding the capacity of the second wheel [4, 8].

## 2. A functional analysis of the process of tyre temperature control

In the previous article written by the team of authors the functional features of direct and indirect options of TPMS were analysed [2]. The authors addressed the problem with the calibration of TPMS by means of technical testers; they likewise conducted traction tests, recording the traction attributes for a simulated tyre pressure decrease in both cold and hot tyres. Determination of thresholds for generating emergency and warning signals for the particular car was analysed in a previous article penned by the team of authors [5].

The subject of the present paper refers to a functional analysis of the system of direct measurement of temperature inside a tyre while generating an on-line signal with a possibility of data visualisation in a separate place among indicators of a car. The possibility of modification of TPMS inference process in terms of early identification of excessive temperature rise prior to exceeding acceptable limits – thereby limiting the effects of destruction of a tyre and reducing the risk of accidents – likewise was indicated. Most applied sensors likewise enable a measurement of a tyre temperature in the range -40°C up to 125°C. The progres-

sive development of TPMS is shown on the example of a product manufactured by Continental that put forward a solution with an immediate user notification on the mobile phone after detecting exceeding the limit values of the measured parameters. The appropriate iTPMSystem application or TPMS application downloaded from the Apple Store and installed on your mobile device analyses and displays data on the screen [3]. It is possible to establish limits for the minimum and maximum pressure level and the maximum temperature level of tyres. In case of emergency a graphic message is sent, indicating the level of emergency or a need for an immediate intervention. Currently used testers allow one to control all sensors installed in wheels and the outcome of the check is the actual level of tyre pressure, temperature, battery status and ID sensors [6]. An important aspect expressing the trend of market needs consists in the possibility of sensor programming both in the case of failure of the existing sensor, as well as the introduction of a new set for seasonal change of car wheels. After having undertaken this procedure it is necessary to run a temperature and pressure test in line with indicators of sensors [7].

The research carried out by many research centres has been focused upon improving indirect TPMS systems for the control of parameters considered as terminal, with the use of measurement of vibration acceleration on individual wheels during load changes while performing traction manoeuvres. Severe disadvantages of such solutions is a production of an alarm signal with a delay, when change of the control parameter exceeds the limit value by about 20% [5].

## 3. TPMS traction tests

An essential notion expressing functional features of TPMS relates to the possibility of quick estimation of a warning signal indicating the state of emergency of a tyre. For purposes of this evaluation traction tests of a vehicle equipped with TPMS were carried out. The P409 sensors with TH9P409S measuring module operating at a frequency of 433,92 MHz were used in both cases in order to measure the temperature in range - 30°C to 120°C and the pressure up to 535 kPa value (Figure 1). An activation of these sensors does not require the use of an external tester since due to an enforced reduction of pressure in subsequent tyres below 1 bar, the system triggers an ID code.



*Source: own research / Źródło: opracowanie własne*

Fig. 1. TPMS P409 sensor (433,92 MHz)
*Rys. 1. Czujnik TPMS P409 (433,92 MHz)*

For the implementation of traction tests on a dry asphalt surface, on a motorway, at the temperature of 32°C two sets of 215/50 R17 95V tyres for the rear axle of a passenger car were prepared. The first set comprised brand new tyres; the second one, however, comprised 63 thousand km mileage used tyres. Before taking measurement a tyre pressure was put in accordance with the factory recommended value and then in both cases the rear axle of a vehicle was loaded up to its limit specified by the vehicle nameplate. The record of changes in tyre temperature was controlled by indications made by an application for TPMS measurement module. The time of the traction test refers to the adopted test interval in the context of UTQG performance appraisal system developed by the US Department of Transportation (DOT). During the UTQG test tyres are being tested at simulated laboratory stands at a period of 30 minutes in order to be marked with one of three letters: A, B or C. Passing the temperature test corresponds to a given symbolism: A for speed of 115 mph (185 km·h⁻¹), B for 100 mph (160 km·h⁻¹) without passing the test for a speed of 115 mph, whereas tyres marked C failed a trial at a speed of 100 mph. Limit and control data of the temperature inside a tyre for TPMS driver were implemented, taking the following levels: 55°C for $t_{yn1}$ and 65°C for $t_{ynk}$.

## 4. Procedure of diagnostic inference

The process of diagnosing a state of an overloaded tyre or a damage to its structure should be implemented not only by an indication of exceeding the limit pressure and inside temperature. The progressive increase in temperature indicated only at the time of limit states that may occur when a vehicle reaches a considerably high speed at which tyre problem leads to serious traction consequences. In contrast to the data found in a specialist literature referring to the issue of modelling the process of tyre pressure and temperature changes, an attempt was made to modify TPMS inference module [1, 7]. Thus, the process of functional diagnostics of a tyre with regard to an operating temperature should be carried out with participation of an inference module analysing the trend of growth curve of this parameter as a result of on-line signal recording. The trend model of a change of an analysed parameter can be expressed as follows:

$$y_n(v) = y_{no} + \Delta yn * v^{\alpha}, \tag{1}$$

where:
$y_n(v)$ – the value of a diagnostic parameter,
$y_{no}$ – the initial value of a parameter,
$\Delta y_n$ – the intensity of parameter change in the time scale of utilisation,
$v$ – the measure of utilisation - the period of time up to the state of emergency,
$\alpha$ – the exponent specifying the nature of parameter changes occurring in the ranges of measurement utilisation.

A regression model forces the type of proceeding: the parameters of signals in the function of measurement utilisation. A product's service life up to occurrence of an emergency state in an ongoing period of time of temperature rise can be written as follows:

$$v_n = v[(\frac{y_{nK}}{y_n(v)})^{\frac{1}{\alpha}} - 1], \qquad (2)$$
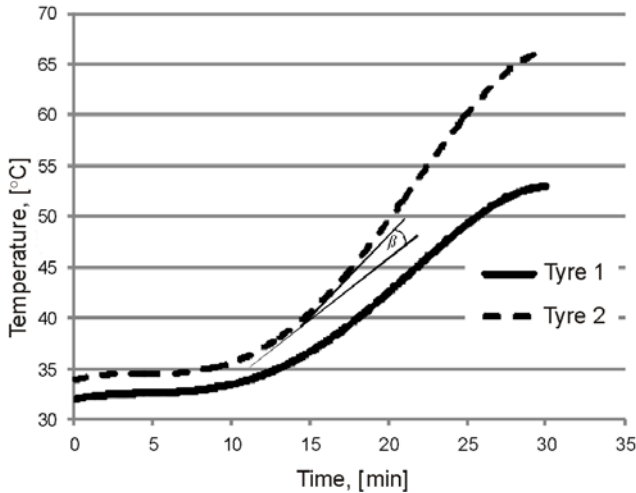
where:
$V_z$ – a product's service life,
$V$ – an interval of parameter variation between the permissible and limit value,
$y_{nk}$ – a diagnostic parameter limit value in relation to $y_{n0}$,
$y_n(V)$ – a control value of a diagnostic parameter.

A graphic representation of intensity of changes in a diagnostic parameter in function of time for a tested car tyre is given in Fig. 1.

Fig. 2. Timing of tyre temperature changes due to its overloading: 1 - the process of even temperature rise for a brand new tyre, 2 - an accelerated temperature rise of an excessively exploited tyre
*Rys. 2. Przebieg czasowy zmiany temperatur opony wyniku jej przeciążenia: 1 - proces równomiernego przyrostu temperatury dla opony fabrycznie nowej, 2 - przyspieszony przyrost temperatury opony nadmiernie wyeksploatowanej*

A determination of an object's limit state parameter solely on the basis of $t_{ynk}$ ordinate value is a considerable simplification of the process of diagnosis. The individual properties of the object are relevant in the initial state at $t_{yno}$ ambient temperature conditioning the rate of temperature increase of a tyre to $t_{yn1}$ control condition. An indication of a bad technical condition of a tyre should occur prior to $t_{ynk}$ temperature on account of the fact that its breakdown may occur before reaching the state limit temperature. Hence, a used tyre with worn tread and damaged cord plies does not retain a nominal capacity which results in a rapid increase in temperature. Furthermore, the appearance of elevated temperature of a tyre for an extended period of time of its utilisation operates as a factor in a progressive destruction of a supporting structure of a tyre. Therefore, it is essential to conduct a thermal performance of a tyre before the range of $t_{yn}$ variability is met (highlighted in Figure 2).
The k(MN) average curvature of MN arc in line with Figure 2 has been analysed as the absolute value of an arc measure of ß angle between tangents in M and N in relation to the segment /MN/ as:

$$k \left[ \overline{M\,N} \right[ = \frac{|\beta|}{|\overline{M\,N}|}. \qquad (3)$$

Maintaining the continuity of a signal allows to record a rising trend of $y_n(V)$ parameter in the time period t.
Thus, the analysis of k(MN) curvature at control intervals fixed by curvature of an arch comprises the process of parameter estimation for functional diagnostics of the utilisation process of a tyre. While narrowing the control range, i.e. when the point N drifts to the point M, we determine the position of the centre of curvature of the MN arc. The curvature of the described range is equal to the inverse radius of $R_M$ curvature.
If the curve equation is written in the form y = f(x) and the f(x) function is the second derivative, the radius of curvature in the range M (x,y) of this curvature is expressed by the following relation:

$$R_M = \frac{[1+(\frac{dy}{dx})^2]^{\frac{3}{2}}}{\left|\frac{d^2y}{dx^2}\right|}; \; where: \frac{d^2y}{dx^2} \neq 0 \qquad (4)$$

If the y=f(x) function has an extremum at the point $x = x_0$ and so when $(\frac{dy}{dx})_0 = 0$ then $k_M$ curvature equals to the absolute value of the second derivative at this point:

$$kM = \left|(\frac{d^2y}{dx^2})_{xo,yo}\right|. \qquad (5)$$

The $k_M$ curvature at the point M is the limit of the average curvature of the MN arc of this curvature when the point N drifts to the point M as noted:

$$k_M = \lim_{M \to N} k(MN) \qquad (6)$$

At a non-linear range, an approximation assumes an exponential form in line with the generalized record, we determine the radius of curvature:

$$R = \frac{(1 + (2ax_o + b)^2)^{\frac{3}{2}}}{2|a|}. \qquad (7)$$

At the apex of the parabola of the severed $x = -\frac{b}{2a}$ we have y'=0 and accordingly $R_W$ is equal:

$$R_W = \frac{1}{2|a|}. \qquad (8)$$

Thus, an assessment of the change trend of a diagnostic parameter coincides with an assessment of changes in the radius of curvature referring to the nature of the temperature ramp course of a tyre before it reaches the limits established for an analysed tyre. In case of a drastic change in the temperature ramp course, that is the rapid elevation of an $t_{yn}$ ordinate, we can already define a state of destruction of the object. The occurrence of damage to the supporting structure of the tyre (curve no. 2) results in a rapid increase of ordinates with respect to mileage of a new tyre (curve 1) with a nominal load of a tyre in both tests.

A regression model requires significant clarifications for an utilisation condition according to a curve no. 2 not to result from an utilisation of a tyre with an incorrect operating pressure. This condition must first be detected by use of an inference module, giving the signal of an incorrect level of tyre pressure. Observing the trend of variation of curvature of time curve at a satisfactory level shall indicate and distinguish threatening conditions of an object. The essential criterion of the diagnosis refers thus to the process of distinguishing of an utilisation of a tire of a proper technical condition in relation to a used one with a progressive damage of cord plies or a shoulder zone of a tyre. The TPMS control system driver should identify occurring utilisation conditions of a tyre, assessing the trend of an internal temperature ramp course before the limit $t_{ynk}$ temperature occurs.

## 5. Conclusions

A priori determination of the limit value of an ordinate of an utilisation parameter, i.e. the temperature of a tyre can be a source of diagnostic errors of TPMS in shape of a delayed identification of a state of emergency.

There is a possibility of an on-line using the diagnostic inference module for an implementation of procedures of enhanced functional diagnostics of an utilisation condition of tyres.

It is necessary to fully identify the object in the following areas: symptom – the value of a diagnostic parameter in relation to a vehicle considered and used type of tyres.

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