On Tire Monitoring Systems Temperature Compensation

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ABSTRACT


The authors previously proved that Tire Monitoring must be focused on the tire (i.e.: vehicle) dynamical behaviour [2], real aim of the supervising action: then even the external absolute pressure must be taken into account.

NHTSA studies showed improper warnings must be avoided in order to keep the driver confidence with the system; internal temperature fall down is the Tire Monitoring Systems' improper warnings main cause.

A new approach for optimal Tire Monitoring Systems temperature compensation related to external environmental temperature, able to avoid improper warnings, will be presented.

INTRODUCTION

Especially due to the recent TREAD Act, November 1st, 2000, Tire Monitoring Systems are now finally getting a wide spread into the market.

Tire Monitoring Systems were originally developed to detect and limit wheel (and vehicle) damages due to tires failures and blow outs. According to NHTSA evaluations [1], Tire Monitoring Systems can be classified into 2 main families: direct (pressure sensor based) and indirect ("wheel speed based") systems. Indirect systems are cheaper but strongly limited in performances.

State of the art direct Tire Monitoring Systems design is usually based on the simple tire internal inflating pressure measure and supervision, eventually tire internal temperature $T_i$ compensated.

Then all the main parameters which deeply affect tire dynamical behaviour are not taken into account: thus it can be stated that such systems are not really focused on tire dynamical behaviour supervision, very important for the whole vehicle safety of use.

Furthermore, the measures realized with state of the art Tire Monitoring Systems often result affected by important errors.

The authors studied accurately the tire wheel working conditions monitoring problem in order to develop effective new design guidelines for next generation Tire Monitoring Systems.

An effective tire supervision action must not be focused on monitoring the simple tire internal pressure but on its final dynamical behaviour. During previous works [2] it was explained that such ambitious task can be achieved monitoring both the tire internal inflation absolute pressure $p_{ia}$ and the external environment absolute pressure $p_{ea}$ in order to obtain a precise value of the tire internal relative pressure, defined by the authors as Inflation state $IS$:

$$IS = p_{ia} - p_{ea}$$

Studying all the basic tire dynamical behaviour equations law it is absolutely clear that, for a given tire and a given vehicle, the Inflation State results the main parameter [2,3]: thus from the inflation state IS value we can achieve effective information on the whole tire wheel tire dynamical behaviour.

Monitoring the inflation state IS is then possible to supervise the tire dynamical behaviour with adequate precision.

The need to monitor both absolute pressure values becomes clearer observing the inflation state IS definition: in fact, since $p_{ia}$ and $p_{ea}$ are continuously varying (with separate law) quantities, even in absence of tire inflating gas leakages, the inflation state IS (thus the tire dynamical behaviour too) is continuously varying. Furthermore, the tire inflating gas leakages are always present and exalt the phenomenon.

Under normal working conditions, the tire can be evaluated as a constant volume system [3]. Then even the internal gas temperature $T_i$ affects the inflation state IS: in fact, for a given internal gas quantity, the internal inflation absolute pressure $p_{ia}$ depends from $T_i$. 
For what concerns the $T_i$ influence on internal inflation pressure, observing state of the art Tire Monitoring Systems, the design community (automotive, aeronautics, tire manufacturers) results separated into 2 main theories.

Several systems compensate the internal inflation pressure value sensed with a $T_i$ measure, obtaining some kind of “internal gas quantity” measure, distinguishing the internal inflating pressure variations due to internal temperature from the ones caused by internal gas leakages. Such solution avoid detection of improper warnings [1] due to fall down of internal gas temperature (reversible) instead of gas leakages.

Other systems adopt a different approach; since tire dynamical behaviour depends from its internal inflating pressure and there is an inferior limit value under which the tire working condition is no more allowed, the internal temperature compensation is then considered wrong: only the internal tire pressure has to be evaluated.

It is the authors opinion that such practice, especially if properly referred to the real inflation state value and not on the simple internal inflation absolute pressure (as proved in previous experiences [2]) results more correct. Unfortunately, the wide internal gas temperature variation leads to an excess of warnings, with a subsequent loose of the user confidence in the system, as NHTSA studies correctly pointed out [1].

Thus, following the requirements to avoid improper warnings and to supervise tire dynamical behaviour, both approaches appear theoretically incomplete and inadequate for an effective practical implementation.

In this paper a new Tire Monitoring approach, based on a novel temperature compensation strategy, referred to the external environment temperature $T_e$ and not the internal gas temperature $T_i$ will be presented. Such approach has been developed in order to satisfy all the requirements new generation Tire Monitoring Systems must follow, both for correct technical formulation and for final customer satisfaction of use.

This temperature compensation methodology must be evaluated as integration of Tire Monitoring Systems design guidelines focused on tire dynamical behaviour supervision.

**STATE OF THE ART**

To correctly approach the Tire Monitoring Systems Temperature Compensation problem, it is first advisable to describe shortly the main knowledges necessary for a complete evaluation.

Tires are the only physical link between the ground and the vehicle. Their main functional tasks are:

- Support vehicle loads
- Grip: driving and braking torque transmission
- Handling: path following force transmissions
- Comfort: ground harshness smoothening and damping
- Total energy losses reduction (application costs).

Such tasks are realized through tire deformation. Actually, tires are very robust, well engineered products, but they must be used properly (i.e.: inside a working state field where their dynamical behaviour is suitable).

In fact, tire intrinsic robustness and ability in working "apparently well" even when strongly under inflated, combined with users incapability to recognize the tire dynamical behaviour decay leads to an overall confidence excess.

As a consequence of such confidence excess, tire prescribed controls result performed less regularly: according with NHTSA, even more than 70% of ground vehicles tires run underinflated. [1], then with not only superior failure and accident risks, but even with higher tire wear, fuel consumption and an overall vehicle handling decay.

Nevertheless, tire working state is continuously varying, depending from environmental and vehicle conditions and must absolutely be kept inside a correct field for satisfactory dynamical behaviour thus not compromising vehicle safety of use: tires optimal operating conditions are important not only for vehicle safety but also to assure the best performance they were developed for, with a subsequent increase of total product life, superior dynamics and cost reduction, the real target to achieve with a massive introduction in the market of Tire Monitoring Systems.

In fact, Tire Monitoring Systems are surveillance systems and must warn the driver in case of abnormality (and not only failure).

User - system interaction becomes then a critical point: excess of warnings, apparently unmotivated but really detecting insufficient inflation state, can lead to the driver confidence loss; proper strategies are then required.

Various studies related tire bearing action mainly with its inflation pressure [3], the authors pointed out [2] that such inflation pressure must be evaluated as the inflation state $T_{IS}$, alias the difference between internal inflation absolute pressure $p_{ia}$ value and the external environment absolute pressure $p_{ea}$ value.

The inflation pressure value is usually measured with a Bourdon tube pressure gauge type differential manometer, whose output is already the inflation state value.

Anyway, such an implicit definition of the physical phenomena has sometimes caused important
conceptual errors in the development of Tire Monitoring Systems and in their system architecture.

To solve this potential cause of errors the authors introduced [2] several new terminologies as well as tire radial deformation trd, inflation state IS and confidence Field.

TIRE RADIAL DEFORMATION TRD

The tire dynamical behaviour is strictly connected and depends from its radial deformation; the tire radial deformation is function of \( p_{ir} \), i.e.: inflation state IS.

To obtain optimal performances (adherence, dynamical behaviour, etc.), tires are designed to react with optimal deformation in function of the operating scenario loads and environmental conditions.

From literature [3], the main design parameter for tire dynamical behaviour is the vertical load to support, \( Q \), which determines the tire deformation, thus adherence, thus wheel dynamical behaviour.

Then, the authors preferred to extend and substitute in their studies the classical radial deflection concept found in literature with the Tire Radial Deformation [2], trd (fig.1) entity: trd results the immediately recognizable, geometrically measurable, final effect of a complex phenomenon connected with the tire contact patch.

![Fig.1- trd: Tire Radial Deformation](image)

In fact, trd is a more extensive concept, connected with the tire wheel dynamical behaviour, the real subject to focus on.

INFLATION STATE

First the authors defined the “flat tire” concept [2]:

A tire can be correctly defined “flat” (i.e.: not able to support loads) when its internal absolute pressure is equal to the external environment absolute pressure.

In other words: a null flow rate condition between the internal tire chamber and the external environment with the inflation valve completely opened.

Using such flat tire definition the inflation state definition \( IS = p_{ia} - p_{ea} \) appear better explained.

The authors also demonstrated [2] the tire dynamical behaviour depends strictly on its radial deformation trd which in turn depends on the tire inflation state IS.

Analyzing tire inflation state it becomes clear that external environment pressure \( p_{ea} \) influences the IS in the same way as tire inflation internal absolute pressure value \( p_{ia} \) does, thus an effective tire monitoring action must absolutely take into account both absolute pressures and not only the internal absolute one [2].

In the previous work [2] was pointed out that the external environment pressure \( p_{ea} \) is continuously and casually varying with relevant percentage variations in function of:

- above sea level altitude,
- weather,
- geographical location
- time.

These variations result not to be taken into account by the Tire Pressure Monitoring Systems design community; in fact, nowadays almost every tire supervision system architecture is affected by the same conceptual error; that’s why they are generally defined as “Tire Pressure” (and not Inflation, nor Radial Deformation, nor Dynamical Behaviour) Monitoring Systems.

To show the relevance of external environment absolute pressure \( p_{ea} \) variations, also considering that a vehicle is used to move into different geographical locations, then altitude variations and weather conditions, a simple example could be of help.

A tire wheel to be maintained at a certain “pressure” value. According to the wheel vertical load literature equations [3], this means a relative pressure value. Imagine, for example a \( p_{ir} = 2000 \) mbar value.

Using a differential manometer for \( p_{ir} \) regulation, the measure output will be the inflation state IS: the instantaneous difference between the internal absolute pressure \( p_{ia} \) and the external environment pressure \( p_{ea} \).

Let then be assumed to regulate \( p_{ir} = 2000 \) mbar in an environment with external absolute pressure \( p_{ea} = 900 \) mbar: then the internal absolute pressure \( p_{ia} \) will be equal to \( 2000 \) mbar + \( 900 \) mbar: \( p_{ia} = 2900 \) mbar.
Fig.2 - $p_{ea}$ variations scenario: altitude and geographical locations

Let all the temperatures be constant, the tire wheel be assumed as perfectly sealed (i.e.: no gas leakage) with constant internal gas temperature $T_i$. The same tire wheel and manometer are now placed in another location with an environment absolute pressure $p_{ea} = 1060$ mbar, (such external environment absolute pressure change is easy to obtain in a relatively short time: weather variations and/or moving some km away are enough).

Then, if the relative pressure measure is repeated, the $p_{ir}$ (i.e.: IS) will be now equal to: $p_{ir} = 2900$ mbar - 1060 mbar = 1840 mbar.

Thus a -8% of $p_{ir}$ (otherwise, more correctly: -5.5% in terms of nominal internal absolute pressure) measure variation occurred without any temperature difference nor gas leakage: the total gas mass (i.e.: number of gas molecules contained in the tire wheel) remained the same.

For tire inflation state check it is necessary to measure both internal and external absolute pressures and to calculate their difference. The authors demonstrated that the use of absolute gauge (like the electronics ones usually present in the TPMS mounted inside the tires) may get wrong results [2].

Another example: begin a travel with a vehicle from a high altitude geographical location (2000 m above sea level) in bad weather conditions: $p_{ea} = 750$ mbar; $T_e = 283^\circ$K. Let the tire wheels be supposed ideal, with no gas losses, inflated before leaving at IS = 2000 mbar; ($p_{ia} = 2750$ mbar) while all the measuring instruments ideal (i.e.: no sensing errors).

Supposing to arrive at a sea level geographical location, with good weather: $p_{ea} = 1060$ mbar, $T_e = 293^\circ$K.

In steady condition also $T_i = 293^\circ$ K, then the internal absolute pressure becomes $p_{ia} = 2847$ mbar while the inflation state IS becomes IS = 2847 mbar - 1060 mbar =1787 mbar.

Then, even in the ideal case of no gas leakage tires, the inflation state is subject to a variation of -10.6%.

Supposing the vehicle provided with a tire inflation pressure (and not inflation state) measuring system, then able to detect only $p_{ia}$ and assuming as reference a constant value in place of external environment absolute pressure $p_{ea}$ (for example: 0 mbar or 1013 mbar), the system will detect only the pressure variation due to temperature variation.

With an absolute pressure gauge, referred to a null reference pressure would be measured the initial $p_{ia} = 2750$ and a final value of $p_{ia} = 2847$: a +3.5% variation.

Otherwise, with an absolute pressure gauge, referred to a 1013 mbar reference pressure, would be measured the initial $p_{ir} = 1737$ mbar and a final value of $p_{ir} = 1834$ mbar: a +5.6% variation.

If those 2 systems were internal temperature $T_i$ compensated systems, they would not detect any variation at all since no leakage occurred (in fact no gas mass variation occurred).

Then, due to external environment absolute pressure variations the tire inflation state and its subsequent dynamical behaviour can change significantly even in absence of internal gas losses or internal gas temperature variation.

Nevertheless, state of the art automotive and aeronautical tire monitoring systems (especially if mounted inside the tire) usually measure internal tire pressure (eventually internal temperature compensated to calculate internal gas mass) [2].

Then they are automatically subjected to intrinsic tire dynamical behaviour evaluation errors: referring to the previous example, a tire pressure monitoring system, not sensing external environment absolute pressure $p_{ea}$, would not detect a significant inflation state difference that really affects the final tire dynamical behaviour, real purpose of the monitoring action.

On the other hand, the same inflation state difference would otherwise be detected during inspection with a (Bourdon type pressure gage like) differential manometer. Furthermore: the 2 measures, even if with no measure errors, would be conflicting.

The error percentual weight depends on the absolute inflation pressure value $p_{ia}$ and often is not negligible.

Moreover, at a first glance, this difference of internal relative pressure observed by differential manometer may be erroneously interpreted as a loss of internal gas pressure, thus a loss of gas.

On the contrary, as described in the example, such interpretation is absolutely wrong: the differential manometer detected a real tire dynamical behaviour variation even without gas leakage and internal absolute pressure change. To solve this problem, several TPMS
manufacturers measure and monitor the internal gas mass, through an internal gas temperature measure and isocore ideal gas law relation, and not only the internal pressure.

Once again: tire internal absolute pressure and dynamical behaviour are not connected. The inflation state IS = (p_a - p_ea) can be used to evaluate the tire dynamical behaviour, real tire monitoring purpose. This must be remembered when designing a tire monitoring

THE CONFIDENCE FIELD

According to the authors [2], the tire and vehicle manufacturers specifications are not excessively detailed and completely defined.

For example, car manufacturers provide (and usually only in the car instruction manual last pages) brief but complex prescriptions about changing tires p_i value in case of vehicle load change and/or different speed run: such recommendations are too complex to be really observed and often even unknown by the drivers.

Moreover, tire pressure regulation indications lack of complete tolerance field prescriptions [1] and usually all the data concerning the use of differential or absolute manometer and the instrument precision and accuracy are not specified [2]. Furthermore, indications related with the environment condition for a correct measure are not clearly prescribed.

Then it is reasonable to think tires are developed to work efficiently in a proper trd field and not in a single value case.

Actually, as a matter of fact, longtime experience acquired on billions of tires proves them really able to work well until trd, or, better, IS, is comprised inside a relatively large “confidence field” set around a nominal value.

Usually an inflation pressure p_i (i.e.: p_ir) nominal value (“placard pressure”) is given by the tire manufacturer related to a given load.

More correctly, inflation pressure must be substituted with inflation state concept, more precise. So, tire is then defined overinflated when its inflation state is higher than the inflation state nominal value, underinflated when lower.

Then for optimal tire supervision is necessary to identify the trd, or IS, confidence field inferior and superior limits. The confidence field upper limit (CFUL) is at least equal or superior to inflation state nominal value. Inside IS nominal value and the CFUL interval the tire is overinflated. The confidence field lower limit (CFLL) is at least equal or inferior to the inflation state nominal value. Between IS nominal value and the CFLL the tire is underinflated. Between the inflation state upper and lower limit the tire results overinflated or underinflated, but with an acceptable dynamical behaviour.

As previously written, a tire inflation state IS continuously changes: once nominal inflation state value is assured (for a given temperature T_i and referring to external environment absolute pressure p_ea), many factors, independent from further inflation (or deflation!) actions, can modify such state in both directions:

- internal gas temperature T_i variations
- external environment absolute pressure p_ea variations
- internal gas mass variations due to gas losses (natural or accidental)

Internal gas temperature T_i variations affect internal absolute pressure value. It is universally accepted that in normal tire use condition the internal tire chamber volume V can be considered constant: the overall volume variation due to tire radial deformation is negligible.

Then, applying the perfect gas law, it is clear that internal absolute pressure and internal gas temperature T_i are linearly related:

\[ p_a / T_i = \text{const} \]

Since in normal ambient condition T_i = 293 °K it can be assumed that the internal absolute pressure p_a variation due to temperature T_i variation is about 1% every 3 °K.

Then, since internal temperature variation occur both for tire ground friction, brakes radiative heat transfer or for external ambient temperature T_e variation, it is clear that even internal absolute pressure p_a is subjected to change as well. Therefore, inflation state IS can change even for internal gas temperature variations.

For what concerns the variations versus, inflation state can be:

- increased mainly due to internal temperature growth and/or p_ea decreases;
- decreased due to internal temperature drop and/or p_ea increases and always from gas losses.

The real problem becomes the identification of the inflation state confidence field limits values.

Observing the inflation state increasing factors it can be stated that overinflation cannot easily reach danger situations.

In normal condition of use tire temperature reaches with great difficulty tires structures safety limits: normally, the carcass and tread temperature is always lower than 80 °C, even with the highest environmental temperatures, thus a maximum increment of 60 °C respect to the nominal inflation temperature occurs.
Tire and wheel structure temperature variations induce internal temperature $T_i$ variations as well, but with delay and smoothening: then, internal inflation absolute pressure $p_{ia}$ variations caused by the internal temperature $T_i$ are usually slower than tire temperature variations. So, the internal absolute pressure increment (at steady state, then after a relatively long time in steady conditions) is not higher than 20% (i.e. for a nominal $p_{ia}=3$ bar, the maximum absolute pressure reached is 3.6 bar).

Inflation state decreasing factors are more important and critical.

In a tire wheel the natural gas losses are always present and directly proportional to inflation state: then, a tire wheel evolves naturally into underinflation, even in absence of punctures or other structural tire wheel defects, getting the inflation state threshold (or the CFLL) in an uncertain and unpredictable time.

As told before, Tire Pressure Monitoring Systems were originally developed for these reasons, aiming mainly at monitoring and warning for sudden deflations and blow outs, certainly important but actually rare cases; on the other hand, tire wheels naturally evolve slowly towards deflation, and nobody notices.

Then, for tire dynamical behaviour supervision the main task should be to fix a confidence field lower limit, or IS "threshold" as defined by the authors, and detect surely, precisely and immediately, with no delay, when the inflation state falls down under the lower limit.

Tire and car manufacturers current orientation is to consider a CFLL about 20-25% under the nominal pressure.

Unfortunately, they do not specify if the value must be calculated in relation to the absolute $p_{ea}$ or the relative $p_{ir}$ pressure value. Usually the calculations are performed in terms of relative pressure: if the nominal value for $p_{ir}$ is 2 bar, then a lower limit at 75-80% of 2 bar (1.5-1.6 bar). Calculating the limit in terms of absolute pressure (3 bar in standard conditions for the given example), the limit will be at 75-80% of 3 bar, that is 2.25-2.4 bar (absolute pressure) equivalent to 1.25-1.4 bar relative pressure in standard conditions ($p_{ea}=1013$ mbar).

Obviously, the precision and accuracy of the threshold sensing instruments must absolutely be much better than the overall inflation state confidence field extension and admitted instruments measures tolerance.

TIRE DEFLATION CAUSES

Gas leakage is the main reason of tire dynamical behaviour decay. Gas leakage is inevitable and it is due to:

- Natural causes (molecular migration through tire and seals rubber):
  - always present on every inflated tire
  - relatively slow gas loss rate
- Accidents (gas leakage from gaskets, tire puncture, hazards…):
  - casually present
  - generally give faster loss of gas, sometimes rise to very high leakage rate (blow out)

Moreover, it is important to remember that natural gas leakages are not the only reason of inflation state IS variation, thus tire dynamical behaviour variation: in fact, inflation state IS varies continuously, and especially lowers down, for $p_{ea}$ e di $T_i$ variations.

External environment absolute pressure $p_{ea}$ variations effects on inflation state IS were already described; the $T_i$ influence on inflation state was evaluated as about 1% internal inflation absolute pressure $p_{ia}$ variation every 3°K.

For example, if a tire is inflated with an inflation state IS value of 2000 mbar after a high speed run with high vehicle load ($T_i=318°K$) and the vehicle is then parked outside during the night ($T_i=T_e=273°K$) even in case of no leakage the inflation state IS variation results about 15% (300 mbar).

Such synergical effect could then become very important.

TEMPERATURE COMPENSATION

Monitoring tires working conditions through their inflation state IS, thus taking into account even the external environment absolute pressure $p_{ea}$ values, was described in detail [2]. The preliminary discussions described must serve as a knowledge basis to completely understand the temperature compensation thesis further developed.

Thus the authors will now focus only on the $T_i$ effects on internal inflation absolute pressure $p_{ia}$ (or, in second instance, $p_{ir}$), evaluating for a better comprehension as null all the external environment absolute pressure $p_{ea}$ variations.

According with NHTSA [1] and taking into account the above mentioned statement, the authors think Tire Monitoring Systems’ main function is to warn the driver if (and when) the tire working conditions are exceeding the inflation state confidence field (then the tire dynamical behaviour confidence field).

Usually, it is very difficult and rare to observe inflation state confidence field limits trespassed in the upper level, while it results normal trespassing the lower limit when the inflating pressure (or, more precisely: the inflation state IS) lowers down. In fact, as previously told, tires
evolve naturally towards underinflation and reach, quicker or slower, the threshold limit.

State of the art Tire Monitoring Systems measure internal inflation absolute pressure $p_{ia}$ value and then obtain the $p_{ir}$ value subtracting from $p_{ia}$ a constant reference value, as well as 1013 mbar, instead of external environment absolute pressure $p_{ea}$.

Thus state of the art Tire Monitoring Systems are not able to really monitor inflation state IS, real purpose of the supervision. Then, for a really effective safety action, the authors recommend the adoption of Tire Monitoring Systems which obtain information on the inflation state IS value from the differential value ($p_{ia} - p_{ea}$), actually the difference of 2 measures: the internal inflation absolute pressure $p_{ia}$ value and external environment absolute pressure $p_{ea}$ value; the $p_{ea}$ value in fact can affect deeply the whole IS measure precision.

Internal inflation absolute pressure $p_{ia}$ value (otherwise $p_{ir}$ following state of the art systems measuring procedures, which evaluate $p_{ea}$ as constant), depends from $T_i$ and, as stated before, varies of about 1% every 3°K $T_i$ variation, assuming the tire as a constant volume system.

INTERNAL GAS TEMPERATURE VARIATIONS AND IMPROPER WARNINGS

$T_i$ caused $p_{ia}$ variations (then $p_{ir}$ or IS) can assume relevant values, eventually increased with external environment absolute pressure $p_{ea}$ variation contribute, not evaluated now. In the case of lowering variations such effect becomes even more critical.

Furthermore, since such $T_i$ (and $p_{ea}$) variations can be rather fast (quicker than natural causes pressure loss), they can be erroneously interpreted as tire failure or blow out effect, even if they can happen in total absence of leakages (just for simple thermodynamical effects).

Such phenomenon can lead to important consequences, especially if associated with TPMS sensors scarce precision and the natural gas leakages, always present in a tire wheel.

In order to better explain the problem, it is first necessary to note that a tire, working in a given vehicle, tends naturally to reach a thermal equilibrium condition with a average temperature value higher than the environment one.

NHTSA [1] reported that in a typical passenger vehicle tire pressure rise up from 0.15 to 0.35 bar during normal operation.

Since tires are excellent thermal insulators, tire gas generally will reach a steady state operating temperature regardless of ambient conditions.

The implication of this is that tire gas temperature and pressure will rise more on a cold winter day than on a hot summer day.

It is important to distinguish between tire structure temperature and tire internal gas temperature $T_i$, responsible of $p_{ia}$ variations.

Tire structure temperature depends on the rotation friction (tread), on the cyclic radial deformation (tire sidewalls), on the thermal exchange between the tire itself and the environment air and ground, and, finally, in second order, on thermal exchanges with the rim, the braking apparatus and the wheel shaft.

In steady conditions, due to the vehicle dynamics actions, the tire structure instantaneous temperature continuously fluctuates in an interval around such average temperature value. The time needed to reach the thermal equilibrium can be evaluated in several minutes of working state [1].

Moreover, it is useful to remember that in normal working conditions (i.e.: IS value included in the confidence field, higher than threshold value) a tire never reaches temperatures high enough to risk thermal degradation. Actually, a tire temperature very rarely reaches 80°C.

Then, the natural tire temperature rise in normal working conditions is not particularly dangerous, exception for extreme cases of long improper use run (where excessive tire temperature rise can lead to thermal degradation and final burn).

At the same time, the tire internal gas is subjected to $T_i$ temperature variations due to the heat exchange with the surrounding tire structure and rim.

Such temperature variations result slower and smoothened compared with the tire structure ones: in fact the internal gas is a natural insulating media.

Then, during steady state conditions, even the Internal gas temperature $T_i$ fluctuates around an average temperature value higher than the outer environment temperature $T_e$.

Within the purpose of this paper, it will be later clear that it is not important to realize if (and how much) such steady state condition internal temperature $T_i$ is considerably influenced from the outer environment conditions: it is important to note that its value is higher than $T_e$.

Then, assuming a vehicle starting to run after a stop (long enough to permit its tires temperature and internal gas temperature $T_i$ to equalize the external environment temperature $T_e$ value: at least 1 hour [1]), it can be stated that the tires temperature and, subsequently, the internal gas temperature $T_i$, will rise up until a steady state value,
higher than external environment temperature $T_e$, will be reached.

On the other side, tires temperature and the internal gas temperature $T_i$ can lower down only through thermal exchange with the soil and the outer environment air $T_e$; in fact:

$$T_e \leq T_i.$$  

Actually, only in few case, and short time, can happen that $T_e$ result (slightly) higher than $T_i$; for example in case of vehicle stopped in steady state condition and external environment temperature $T_e$ rising up: in such a situation the delay due to the thermal exchange between the environment and the internal gas may really realize the $T_e \geq T_i$ condition

However, the external environment temperature $T_e$ rises slow and only of few degrees ($^\circ$K) in quite long time; later it will be shown that these rare and temporary conditions have a positive effect in tire monitoring using the temperature compensation strategies proposed by the authors (in fact such situations increase the level of safety).

In any case, $T_i$ can lower down only through thermal exchange with heat release by the tire to the outer environment.

Appreciable $T_i$ variations, then able to change significantly internal inflation absolute pressure $p_{ia}$ and relevant for tire monitoring, appear mainly when the vehicle is parked for a long time (hours) in an environment with temperature much lower than the nominal value (i.e.: 20°C or the $T_e$ value during inspection/inflation)

Typical, and very common, situation is when the vehicle is parked outside during night. Usually tires are checked in a gas station or specialized center, typically located few kilometers away [1]. Then it is reasonable to say that the tires check is performed with tires already warmed up due to previous rolling, thus their temperature is not particularly far from the nominal value, if not higher in case of longer run. Then, during night, the environment temperature $T_e$ can easily drop down of 20-30°C respect to $T_i$ value during check/inflation.

During outside park stop the internal gas temperature $T_i$ can lower down of about the same variation of external environment temperature $T_e$ (after some hours a steady state thermal equilibrium is reached with $T_i = T_e$)

For example: if the internal gas temperature $T_i$ variation is equal to 30°C (as can happen in most european and northamerican countries) the subsequent internal inflation absolute pressure $p_{ia}$ lower down variation results of about 10%.

Further example: assuming the internal inflation absolute pressure $p_{ia}$ checked at $p_{ia} = 3000$mbar (IS=2000mbar if $p_{ea}=1000$mbar) with a $T_i = 35^\circ$C (a few kilometers run is enough to reach these values) and a night external environment temperature $T_e = 5^\circ$C: the next early morning a internal inflation absolute pressure $p_{ia}$=2700mbar will be noticed, with a $p_{ir}$ (IS)= 1700mbar (in case of $p_{ea}$ =1000mbar: no $p_{ea}$ variation otherwise could be even worse!), then a 15% $p_{ir}$ variation!

As written before, manufacturers usually assign a confidence field threshold value 20-25% lower than $p_{ir}$, nominal inflation relative pressure (IS); referring to the example made, such threshold value would be 1600mbar (20%) or 1500mbar (25%). Then the confidence field amplitude would be 400 or 500mbar under the nominal value.

Moreover, when studying tire pressure (or, better, inflation state) supervision, it must be noted that both the instruments used for inspection check and the instruments used for tire monitoring are subjected to errors and measurements imprecisions.

The magnitude order of such errors and deviations is, usually, of several percent points. Then, their effect on the monitoring and measuring action is easily determinable and leads to a further reduction of the effective confidence field to rely on to assure real safety conditions.

This problem must be noted and adequately taken into account when evaluating the Tire Monitoring problem, but, as well as done with the $p_{ea}$ variation, assumed null for easier comprehension of this paper topics, the authors at the moment prefer to assume all the instruments as perfect instruments (i.e.: no errors).

Then, referring to the previous example, assuming to fix the threshold value (i.e.: the driver warning value) at a 1600mbar value, it can be noted that the simple effect of the night cool down on the external environment temperature $T_e$ can reach a p ir value of 1700mbar. Then the tire results still inside the confidence field, no warning signal must be sent to the driver.

It is easy to realize that a stronger temperature variation could be enough to overcome the warning threshold, even assuming perfect instruments, null variation of external environment absolute pressure $p_{ea}$ and absolutely no tire leakages. Referring to the example, if the tire check would be performed with $T_i=45^\circ$C and during night $T_e=0^\circ$C, $p_{ea}$ would fall down of 15%, then to 2550mbar; $p_{ir}=1550$mbar.

In this case, the warning signal must be sent. The driver would be surprised, remembering he checked the tires the day before. Going back to the tire check station, then driving for several kilometers, the internal gas temperature $T_i$ would rise up to, for example, 15°C: then the tire would result with a $p_{ir}$=1700mbar, inside the
confidence field, contradicting the Tire Pressure Monitoring System. The daily repetition of this case would finally lead the driver to lose faith in the system.

This phenomenon can happen even more subtle: in fact, with the contribute of real natural gas losses, $p_{ea}$ variations and instrument errors the critical external environment temperature $T_e$ variation can be much lower.

Still referring to the example, introducing a natural gas leakage equal to 1% of internal inflation absolute pressure $p_{ia}$ per month, it would be noticed a 30mbar pressure drop, then equal to 7.5% of the whole confidence field (400mbar).

Considering an external temperature lowering (referred to the inspection check external temperature), of 24°C, due to night cool down, the subsequent internal inflation absolute pressure $p_{ia}$ variation occurred would be 8%, then equal to 240mbar: 60% of the whole confidence field.

Thus, after $(1-0.6)/0.075=5.3$ months, the system would warn the driver every morning. Let imagine the inflation pressure checked (5.3month before) with $T_i=30°C$ ($303°K$). Then, if the driver proceed to check tires only after they warmed up for some hours (and/or after several high speed run) it would be found $T_i= 40°C$ ($313°K$), then $p_{ia} = (3-(0.075*5.3))\times(313/303) = 2.69bar$, with a $p_{ia}$= 1690mbar still inside the confidence field.

It is useful to remember that such examples were developed under strong inapplicable conditions: the presence of perfect instruments and, even worse, null $p_{ea}$ variations.

Once again, the continuous warning signals may lead to loose the driver’s confidence on the system.

The danger to loose the “user trust on the system”, already noticed in many state of the art TPMS application was observed and described by NHTSA [1] which suggests Tire Monitoring Systems manufacturers to avoid to send too often (and/or too early respect to last inspection check) “improper warning” signals.

An “improper” (“false” according to NHTSA [1]) warning can be defined as a signal occurred because the inflating pressure went below the threshold for the only internal gas temperature $T_i$ lowering, due to long exposition to low external environment temperature $T_e$.

Actually it is true the inflation pressure (better: inflation state IS) is really under the threshold value (i.e.: the tire results underinflated), no matter the reason (temperature cool down, gas leakages, external environment absolute pressure $p_{ea}$): the aim is supervise tire dynamical behaviour. But, at the same time, if the inflation pressure (inflation state IS) goes under the threshold value for external environment temperature $T_e$ cooling down, such phenomenon appear only when the vehicle is parked for a long time in a cold environment; as soon as the vehicle runs, all the friction actions warm the tire up and restore acceptable inflation state IS conditions.

Then, after a few minutes run, the inflation state reaches the allowable confidence field.

Thus, the inflation pressure lowering due to temperature cooling down leads to a real under threshold state, but it is definitely a temporary condition, acceptable inflation state is quickly restored. For this reason such warnings, caused by temperature lowering down and not gas losses, are defined “improper”.

As already written, instrument precision errors can considerably contribute to false warning generation, NHTSA as well recommend the adoption of high precision sensing instruments in Tire Pressure Monitoring Systems. Precision errors can lead to important percentage erosions of the whole confidence field, increasing the problem difficulties.

TIRE PRESSURE MONITORING SYSTEMS
TEMPERATURE COMPENSATION STRATEGIES

Avoiding improper warnings becomes then another difficult feature to implement in Tire Monitoring Systems. Some TPMS manufacturers tried to solve this problem compensating the inflation pressure with the internal gas temperature basing on constant volume ideal gas law proportionality.

Actually, such systems do not measure only inflating pressure (usually this measure is performed adopting a single absolute, or relative with a constant reference pressure, sensor located inside the tire chamber) but sense also internal temperature $T_i$, then they are theoretically able to evaluate and monitor the gas mass inside the tire chamber.

Supervising the total gas mass, then compensating the inflation pressure with internal temperature, these systems are theoretically able to distinguish between real gas leakages inflation pressure losses and the temperature lowering ones.

Adopting such temperature compensation strategy improper warnings generation is precluded, but only if the inflation check gas temperature is the same considered in the compensation algorithms. However, this solution is not widely accepted.

In fact, part of the automotive manufacturers noted that Tire Monitoring Systems must absolutely detect inflation threshold trespassing, whatever the cause. Then their opinion is to refuse systems adopting an internal gas...
temperature $T_i$ compensation, thus measuring internal gas mass.

Actually such position appears scientifically more correct, especially evaluating Tire Monitoring Systems in terms of inflation state IS supervision, thus tire dynamical behaviour supervision, and not simply evaluating inflation pressure.

However, with Tire Monitoring Systems with no temperature compensation too many improper warnings are generated, with a subsequent loss of the user trust in the system.

To solve this problem, and to take into account sensing instruments precision errors, several systems manufacturers suggest to increase the confidence field (i.e.: lower threshold value), certainly not an optimal solution.

Moreover, it must be noted that gas mass evaluating systems are based on internal gas $T_i$ measure, but this measure results very difficult to be precisely performed.

Usually, Tire Pressure Monitoring Systems sensors are located inside tire chamber and rigidly fixed to the rim through belts or through the tire inflating valve stem.

As everybody knows, a temperature sensor, like the ones used in such kind of application, actually senses its own temperature, in thermal equilibrium with the surrounding environment: its case, fixed to the rim and then only partially in contact with the internal gas.

Then, taking into account all the rim temperature variations (which is, in turn, very close to the braking apparatus), it is reasonable to think that the temperature value really sensed is different from the real internal gas temperature $T_i$, with subsequent unpredictable errors in the compensating action.

Furthermore, the temperature measure realized by the sensor (and in a quite wide range of values), is obviously subject to errors. Such errors further decrease the overall system precision reducing once more the real confidence field available.

It is the authors opinion that a Tire Monitoring System temperature compensation performed with internal gas temperature $T_i$ and state of the art strategies does not guarantee enough precision, on the contrary it is source of further measuring errors.

Moreover, since the tire dynamical behaviour does not depend on the gas mass inside tire chamber [2], monitoring inflation gas mass has no sense for tire monitoring (that must be performed on inflation state supervision).

Moreover, the authors think the optimal solution is to develop a monitoring strategy able to really supervise inflation state, thus tire dynamical behaviour, thus able to detect the threshold value trespass, whatever the cause, and, at the same time, to avoid false warnings generations, especially in the case of pressure lowering due to temperature cooling down.

The authors then developed a novel approach to the problem.

A TIRE MONITORING SYSTEMS TEMPERATURE COMPENSATION NOVEL APPROACH

Such approach is focused on the need to really supervise tire dynamical behaviour (thus the inflation state) but is able to avoid improper warnings generation (due to temperature cooling down) with a subsequent improvement in the monitoring action precision and, at the same time, let the designers the chance to reduce the confidence field, increasing safety conditions.

This novel temperature compensation strategy can be understood looking at figure 3:

\[ \alpha_{IS/T} = \frac{p_{ia}}{T_i} \]

\[ always \geq 0 \]

\[ p_{abs} \]

\[ p_{ia(T_i)} \]

\[ nom. infl. pressure \]

\[ \Delta p_{i_{nom}} \]

\[ \Delta p_{i_{abs}} = IS (T_i) \]

\[ H_{cf}(T) \]

\[ IS cf \]

\[ warning field \]

\[ X \]

\[ 20°C \]

\[ T \]

\[ T_{abs} \]

Fig 3: operating scenario: absolute Temperature $T_{abs}$ vs Absolute Pressures $p_{abs}$ diagram.

The external environment absolute pressure $p_{ea}$ is represented with an horizontal line parallel to the $T_{abs}$ axis; with the blue color region is showed the external environment absolute pressure $p_{ea}$ variation field (and it can be noticed its importance in terms of inflation state).

The nominal absolute inflation pressure (placard inflation pressure) $p_{i_{nom}}$ is imposed at the nominal temperature (ex.: $20°C =293°K$). The sloped line represents the variation of $p_{i_{nom}}$ in function of $T_i$; obviously the line origin is at the ($0°K$, 0bar) point and its equation can be obtained through imposing the line itself to pass the point ($293°K$, $p_{i_{nom}}$).

Assuming the external environment absolute pressure $p_{ea}$ be constant for all of the $T_i$ values, the inflation state IS is then represented as function of the internal...
temperature $T_i$ with a sloped line, parallel to the previous line, with equation $\Delta p_{ea} = p_a - p_{ea}$.

Under this hypothesis, this curve can be defined even as relative inflation pressure $p_{ir}$.

It must be remembered that the target of the tire monitoring action is to supervise the tire dynamical behaviour, to be assured higher than the lower threshold value, representing the confidence field inferior limit.

Tire dynamical behaviour is represented by inflation state $IS$.

Then, inflation state must be checked to be higher than the limit value (threshold), representing the confidence field inferior limit.

Supposing $p_{en}$ to be regularly applied, thus without excessive overinflation, it was already exposed that inflation state higher than the nominal value cannot be seen as a problem.

The inflation state value must always be kept over the threshold, whatever the temperature induced variations.

Then, the inflation state inferior limit (i.e.: threshold) is represented with the red horizontal line, (parallel to the $T_{abs}$ line) fixed at the $\tau_0$ value, obtainable at the nominal Temperature (in this case 20°C=293K) located under the nominal inflating pressure value (placard) $\Delta p_{en}$ of a quantity equal to the inferior confidence field extension prescribed by the manufacturer (usually -20 -25%).

For safety, whatever the inflation state value, if lower than $\tau_0$, the warning signal must be sent to the driver, whatever the causes.

The angle $\alpha_{IS1}$ between the IS($T_i$) line and the $\tau_0$ line is always positive. Then, the confidence field amplitude $H_{cf}$ varies in function of temperature, resulting directly proportional.

Then, it can be stated that in the diagram it always exist a point "X" located at a temperature $T_x$, lower than nominal temperature, where IS= $\tau_0$, thus $H_{cf}$=0.

Tire inflation state reaches the X point, and subsequently its minimum allowable value, when the temperature lowers down from the inflation check temperature (in the example 20°C) to the $T_x$ value.

This is the case of the improper warnings examples previously described. If such phenomenon appears too often, like in the case of night cooling down, or other cases as well as the vehicle parked in a snow covered ground, the generation of “improper” warnings occurs. Since such a situation is just a temporary situation, it is autonomously reversible once the vehicle is on run.

Improper warnings must be bypassed. State of the art strategy adopting internal gas temperature $T_i$ compensation on inflation pressure does not appear correct, even assuming as solved the great difficulties in detecting the real $T_i$ value.

Such state of the art strategy can be represented on the diagram simply changing the slope of the $p_i$ line (in this case, with the assumption of $p_{ea}$= constant it is equal to the IS($T_i$) line) making it horizontal (thus parallel to the $\tau_0$ line representing the threshold). In this case, the temperature variation has no effect on the $p_i$ value, even if this conflicts with the tire dynamical behaviour supervision task.

For what concerns the lowering threshold strategy, adopted from those who don’t agree with the gas mass monitoring theory, in the diagram it can be seen as moving the $\tau_0$ point away respect to the $\Delta p_{en}$ point.

In this way, the X point is moved towards lower temperatures, and then greater variations are needed to reach it. Unfortunately the threshold may reach dangerous values, where the tire dynamical behaviour could be not acceptable. Moreover, the threshold is set from the manufacturers who are responsible of the whole tire safety of use.

The authors do not think that current state of the art systems, with $T_i$ temperature compensation and no real external environment absolute pressure $p_{ea}$ evaluation (as written before, these system consider $p_{ea}$ as a fixed constant reference value while is considerably variable), are really effective, but, in order to improve their performances, suggest to modify the actual integral proportion gas law compensation (then with a inflating pressure correction of about 1% every 3K; i.e.: making horizontal the IS($T_i$) line) with a much smaller proportionality ratio.

In fact, it is the authors opinion that a lighter effect compensation law, for example an inflating pressure correction of about 1% every 10K, or 15K, or 20K, (then a smoothened compensation: 15; 20; 30% of the real ideal gas low compensation) would be much better.

In fact, the main effect of such a kind of modified compensation, referring to the diagram, would be to reduce the $\alpha_{IS1}$ angle between the IS($T_i$) line and the $\tau_0$ line: the X point would result shifted towards lower temperatures without lowering the threshold limit (fig.4).

The confidence field amplitude would gradually reduce for temperatures higher than the reference nominal temperature (in this case assumed as 20°C) but without compromising the monitoring action (such amplitude would be always greater than the nominal temperature one). On the contrary, the confidence field would expand towards lower temperatures without modifying the threshold.
Fig 4: modified Ti compensation strategy effect in the operating scenario.

Such temperature compensation strategy, adoptable within state of the art Tire Pressure Monitoring Systems architecture, can be evaluated as really effective only if the temperature compensation is based on the real inflation gas temperature value.

The problems related with real internal gas temperature sensing were already described. Then, this modified strategy can be estimated valid only during almost stationary conditions, for example with a vehicle parked for long time; under dynamical conditions it would certainly result much less reliable.

The modified strategy suggested, still based on the Ti sensing, could be useful in order to avoid many of the improper warnings generated by traditional systems, monitoring only pia. However, the authors already proved [2] this kind of systems have intrinsic functional faults, that considerably limit their performance.

That’s why the authors think it is necessary to leave these strategies and adopt a novel approach.

As told before, measuring the real internal gas temperature Ti results very difficult, even neglecting the problems connected with the sensing instruments precision errors.

Then it seems much more advisable to identify a novel strategy not relying on Ti measure.

Studying the diagram: when the temperature Ti rises up (referring to the temperature nominal value at which the vehicle is inflated imposing the inflation pressure pian) the confidence field amplitude Hcf decreases until becoming null in the X point.

Due to the vehicle run, the internal gas temperature Ti tends to increase, it can decrease only when the vehicle doesn’t move, with a lower external environment temperature Te. In stationary conditions, the thermal equilibrium is realized only when Ti = Te, however the temperature variation case must be studied only when Ti > Te.

Then, a more effective Tire Monitoring Systems temperature compensation strategy must be developed taking into account external environment temperature Te, even easier to measure, and not Ti.

Let be considered the effect of time on inflation state IS (fig.5).

The time axis can be well represented with an oriented line, with origin at the nominal inflation pressure pei point.

For easier comprehension, let pae be still considered constant: then it is possibile to talk of inflation state IS instead of internal inflation absolute pressure pia.

Due to the only natural gas losses the inflation state IS line, with origin at (0 °K; 0 bar), will gradually decrease its slope: in fact the second point the line must pass through is (Δpe, 293°K) where the Δpe value is lowering down for the leakages.

Then it becomes easy to draw (and calculate) the lines envelope representing the inflation state IS time evolution; in figure 5 are visible the IS lines month after month.

Obviously, the same effect is obtainable with accident gas losses (poucures, blow outs...), the only difference would be a much faster, as well as the gas loss is, slope decrease.
Given the $\Delta T_{\text{d/n}}$ temperature drop, there are two ways to increase $t^*$ without taking into account $T_i$ (i.e.: without measuring $T_i$): lowering the threshold $\tau_0$ or realizing a temperature adaptation of the threshold value.

Lowering the threshold $\tau_0$, thus increase the $H_{df}(20^\circ)$ value, is simple to realize but against safety (small $H_{df}$ is better); moreover, the manufacturers prescriptions fix the threshold not less than 20 or 25% under the placard (relative) pressure.

The solution proposed by the authors adapts the threshold values relating them with temperature: in this case $T_e$ (and not $T_i$) is the right reference, being the responsible of the $T_i$ drop.

The adaptation algorithm, taking into account $T_e$ and not $T_i$ (i.e.: the cause and not its retarded effect) is applied not to artificially modify the internal pressure value read by the pressure sensor, but in order to slightly relocate the threshold limit, that can be stated at the right nominal value for the single tire application.

The final effect of this action results then equivalent to the modification of the IS($T_i$) line slope: an “X point” shift towards lower temperatures, in order to postpone the first improper warning due to temperature drops.

Adopting this new strategy, such a difficult task like the internal gas temperature $T_i$ measure (as written before, even perfect sensing instruments would result imprecise: the temperature sensed is not only the internal gas temperature one; moreover, the internal gas temperature has not a constant value, both in radial and in axial sections) is no more necessary.

The new strategy requires to look at the value of the external environment temperature $T_e$, much simpler to sense with adequate precision, and to apply its instantaneous value to correct the threshold limit (and not the internal tire pressure).

The adaptation algorithm could be linear or non-linear and the compensation factor could be small, also in this case.

The authors think that a linear adaptation set around several percent points of the maximum correction (the one able to bring the $\tau_0$ line slope at the same value of the IS($T$) one) will be proper. A correction of about 20 or 30% is reputed enough also for the worst natural deflation ratios in order to assure the respect of the NHTSA recommendations.

In this case, the threshold value at lower temperatures will be only a little bit inferior than the nominal one (less than 3% for a temperature drop of 30 °C).

Observing that using precise and accurate pressure sensors, without significant measure changes with temperature variations or time, it is possible to set the $\tau_0$ threshold value not far from the placard IS value (or, in other words, to set an inferior confidence field limit at a value closer to the placard IS than 20 or 25%; for example setting $\tau_0$ at -15% or -10% respect to placard value, taking into account the real natural gas loss of tires), it will be possible to have the adapted threshold line always over the insuperable limit indicated by the manufacturers (-20% or – 25%). This will improve safety.

Moreover, the solution here proposed improves safety also when the tires internal temperature rises up (moving vehicle) and in case of significant gas loss: a threshold closer to placard IS and positive $\tau_0$ line slope variation shows that when $T_e$ is higher than the nominal value, $H_{df}$ is gradually reduced proportionally to the temperature rise. In case of real gas leakage (tire puncture) the warning will be earlier.

Some other consideration about the threshold values will be useful.

As NHTSA reported in [1], «most pressure-sensor based systems have a two stage warning approach. The first driver notification of underinflation is an “underinflation advisory” meant to inform of low tire pressure that should be corrected at the next available opportunity. The second driver notification of underinflation is a “significant
underinflated warning” meant to inform of a significantly, and dangerously low tire that must be immediately remedied.”

The authors observe that the strategy to use two different threshold may be good, but only if the system (and the sensors) used are sufficiently precise and accurate.

The effective threshold values measured by NHTSA examining some existing system were between -13% and -43% for the first one, and between -31% and -70% for the second one respect to the placard inflation pressure. Average Advisory Threshold: 27% Below Placard, average Warning Threshold: 42% Below Placard.

It is the authors opinion that running with a tire at -70% (or -40% too!) may be absolutely not proper and sometimes very dangerous (fig. 7).

Then, with such a wide error range, complicating the Tire Monitoring System with many warning levels it really does not result very useful. In most cases, a single unambiguous threshold, correctly and precisely identified, may be better.

Thus, the authors strongly believe it is of primary importance to focus on the improvement of sensors and system performances (both precision and accuracy) while developing more complex warning solutions should be evaluated only later.

Furthermore, it is very important to take into account the delay between the physical phenomenon (tire inflation state IS threshold overcoming) and the warning signal transmission.

Only short time delays are admitted, few seconds are acceptable, minutes certainly are not: some punctures have a very fast deflation rate!

According to NHTSA [1], systems with a not quickly enough warning generation can allow tire damage to occur while in the underinflated condition. Fast reaction time is of fundamental importance for this kind of systems.

CONCLUSIONS

Tire Monitoring Systems main target is tire inflation state IS supervision.

A warning must be sent to the driver if IS goes under a preset threshold $\tau_0$, constant with temperature and closest as possible to placard inflation state IS value.

The threshold value $\tau_0$ is specified as a percent difference from nominal (or placard) inflation state $\Delta p_{gs}$: the smaller such difference is the better, but high precision and accuracy are needed.

Inflation state IS supervision is possible only with a relative tire pressure sensor referring to the external absolute pressure $p_{es}$ and able to detect threshold overcoming. A warning has to be sent when $\Delta p_{te} = \tau_0$.

Gas losses and temperature lowering on parked vehicles bring inflation state IS under threshold. In normal conditions, the main problem to solve is the external temperature drop.

The threshold limit $\tau_0$ must be adapted to temperature variations to better satisfy NHTSA request: a time $t^*$ before warning due to natural causes of no less than 4+6 months at least.

To increase $t^*$ is possible to lowering $\tau_0$ to increase $H_{cf}$ (against safety prescriptions) or adapting threshold in relation to temperature variations in order to move the point where $\Delta p_{te} = \tau_0$ towards lower temperatures.

Temperatures involved in the physical phenomenon are the environment external one $T_e$ and tire internal gas one, $T_i$. Internal tire temperature drops when the external one, $T_e$, drops.

The bets temperature to take in account for the $\tau_0$ adaptation is the external one $T_e$, not the internal one $T_i$ or other temperatures.

The strategy ideated to adapt threshold is based on the realization of a $\tau(T_e)$ dependence. This solution improves safety: if $T_i$ rises more than $T_e$, warning is sent always before threshold $\tau_0$; if $T_e$ rises (slightly!) more than $T_i$, earlier warning conditions are present.

A precise and accurate system with threshold adaptation related to $T_e$ should have a long time $t^*$ before warning and a threshold limit always close to the placard IS.

The new approach proposed by the authors may solve both the problems to avoid improper warnings without decreasing safety (in any case, the threshold overcoming is immediately signaled to the driver).
Furthermore, it is evident that the need to read both external (environment) absolute pressure $p_{ea}$ (in order to survey IS, thus tire dynamical behaviour) and external (environment) temperature $T_e$ (in order to apply a ideal threshold adaptation) shows that systems outside tire are better than the ones mounted inside tires.

In case of small mass and dimensions, the outside systems may be better than the inside ones, also for safety (the centrifugal force acting on a mass placed into the tire my be very high). Nevertheless, outside mounting needs antitheft solutions.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$T_i$</td>
<td>tire internal temperature</td>
</tr>
<tr>
<td>$p_{ia}$</td>
<td>tire internal inflation absolute pressure</td>
</tr>
<tr>
<td>$p_{ea}$</td>
<td>external environment absolute pressure</td>
</tr>
<tr>
<td>IS</td>
<td>inflation state</td>
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<tr>
<td>$T_e$</td>
<td>external environment temperature</td>
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<td>trd</td>
<td>tire radial deformation</td>
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<td>Q</td>
<td>vertical load to support</td>
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<td>confidence field upper limit</td>
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<td>nominal inflating pressure value</td>
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