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Impact assessment of an intelligent central tire inflation system for passenger cars

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Abstract

Tire inflation pressure affects vehicle energetic balance, as well as road safety. These issues are particularly critical due to the low attention paid by the drivers to tire maintenance. Tire pressure monitoring systems are used to alert the drivers in case of low pressure, but higher benefits could be obtained through a completely autonomous on-board system capable of setting the optimal tire pressure according to current working conditions and of automatically inflate or deflate tires. Basing on computer simulations on fuel economy of a reference mid-size diesel passenger car, and referring to statistical data on vehicle use, the potentialities of such a device is evaluated on an annual mission. The results are then extended to the whole European fleet to provide an estimation of the potential benefits that could be obtained through massive adoption of this solution. The impact is evaluated through an economical evaluation of: fuel savings, reduction of social cost of carbon emissions, increase of tire life and reduction of costs related to crashes produced by improper tire pressure.

Keywords: tire pressure; central tire inflation system; fuel consumption; road safety; CO_2 emissions.

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Nomenclature

α_R	Coefficient of fuel consumption sensitivity to rolling resistance variations [l/100km]
α_M	Coefficient of fuel consumption sensitivity to vehicle mass variations [l/100km]
C_{rr}	Rolling resistance coefficient [kg/ton]
fc	Average fuel consumption [l/100km]
fc_{year}	Cumulated annual fuel consumption [l]
f_T	Percentage of trips in a class
k_d	Class of travelled distance
k_l	Class of loading conditions (vehicle mass)
k_t	Class of trip duration
M	Vehicle mass [kg]
n_T	Number of trips in a class
p_{inf}	Tire inflation pressure [bar]
SCC	Social Cost of Carbon
t_{roll}	Rolling time [min]
x_d	Travelled distance [km]
x_t	Trip duration [min]

Subscripts

0	Start of trip
CS	Referred to tires cold start conditions
EU	Referred to extra-urban driving mode
U	Referred to urban driving mode
eot	End of trip
nom	Referred to nominal conditions
ref	Referred to *reference* case
$sc\#$	Referred to *scenario #*
$trip$	Referred to the whole trip duration (fuel consumption)

1. Introduction

The increasing technological capability in tracing and using energy resources has fostered the improvement in human wellbeing in the past two centuries. Quality of life and related variables, are correlated to energy consumption per capita (Pasten et al., 2012) as well as to indices related to energy availability, usage and distribution (Lambert et al., 2014). Transporting goods and people also contributed to the improvement of quality of life: the distance travelled by vehicles increased with the growth in the national GDP, although it is not possible to assess the causality between these two variables (Ecola et al., 2012). On the other hand, this development relied on the massive usage of fossil fuels (EIA, 2016), which caused a substantial increase in CO_2 emissions. The transportation sector accounts for 25% of the world's total energy consumption (EIA, 2016) and is responsible for nearly 60% of the global oil demand and 10% of global GHG emissions (Atabani et al., 2011). Moreover, burning fossil fuels also contributes to the presence in the atmosphere of pollutants that cause every year 3.3 million deaths all over the world, 5% of which (165'000 deaths/year) are due to transportation (Lelieveld. et al., 2015).

This scenario forced the automotive OEMs and the legislators to set a limit to the CO_2 emitted by vehicles (Regulation EU No 333/2014). The reduction in fuel consumption passes through improvements in various fields: from the usage of lightweight materials to engine downsizing and improvement to the combustion efficiency, as well as improvements in aerodynamics and reduction of powertrain frictions (Atabani et al., 2011).

Considering a vehicle with reference fuel consumption of 11.5 l/100 km in city driving and 8.6 l/100 km in highway driving, common tires under-inflation causes a worsening in fuel consumption by 0.162-0.216 mpg (0.1-0.13 l/100 km) in urban driving and by 0.216-0.288 mpg (0.07-0.1 l/100 km) in highway driving (Pearce et al., 2007). Taking into account that 78% of the European drivers run vehicles on underinflated tires (Bridgestone, 2013), it is clear that tire inflation pressure has a strong effect on real-world fuel economy and, as a consequence, on CO_2 emissions. The legislator intervention in this field tries to prevent inappropriate drivers' behavior by means of the mandatory installation of TPMSs on new vehicles (Regulation EC No 661/2009) and leads tire manufacturers to produce tires which allow to improve fuel economy (Regulation EC No 1222/2009).

This paper addresses the effect of tire pressure management on passenger cars. An estimation of the fuel consumption variations are provided on an annual basis. The effect of tire warm-up is taken into account, as well as the variations of the loading conditions. The case in which tire pressure is maintained always at the levels indicated by the car manufacturer is compared to misuse cases, and to some pressure management strategies that could be applied through an autonomous on-board tire inflation system capable of adapting the tires to the current working conditions. The effect for a single car in terms of fuel economy, fuel cost and CO_2 emissions is first assessed. Then, the analysis is extended to show the potentialities of the technology if applied to the whole EU circulating fleet, e.g. due to future regulations. An economic estimation is also provided taking into account the social cost of carbon emissions that could be saved through the application of this technology and the possible reduction of tire life in case of improper tire pressure management. Additionally, an active management of tire pressure could avoid road crashes. These costs are quantified in order to provide a general prediction of the economic return which could be obtained by governments and by the European Commission by fostering the diffusion of an on-board technology for autonomous management of tire inflation pressure.

2. Methodology

A mid-size diesel passenger car (1.3 liters turbocharged engine, model year 2010) will be considered as a reference, with fuel consumption $fc_{ref,U}$ = 6.2 l/100 km in urban areas and $fc_{ref,EU}$ = 3.5 l/100 km in extra-urban routes and highway, as declared by the vehicle OEM and based on the NEDC type-approval procedure. The vehicle has a reference test mass of 1285 kg (curb weight, fluids and driver) and a maximum allowed vehicle weight of 1665 kg in full-load conditions, and is equipped with tires with rolling resistance coefficient $C_{rr,nom} = 7.7$ kg/ton, evaluated at a reference tire inflation pressure of 2.1 bar, at 80% of the rated vertical load, at a speed of 80 km/h (ISO 18164). The inflation pressure p_{inf} is always considered as measured under cold tire conditions. Three main effects will be taken into account:

1. The variation of fuel economy performance due to a change in tire inflation pressure, through the relative variation of rolling resistance coefficient with pressure (Fig.1a, reproduced from LaClaire, 2006). For this purpose, the results of some fuel consumption simulations performed at a reference vehicle mass M_{ref} and for a set of tire inflation pressures p_{inf} have been exploited. A coefficient α_R, representative of the fuel consumption sensitivity to variations of the rolling resistance coefficient (Barrand et al., 2008), has been estimated as the angular coefficient of the interpolating function shown in Fig.2a. Two sensitivity coefficients, $\alpha_{R,U}$ and $\alpha_{R,EU}$ respectively, have been calculated on the urban and extra-urban parts of the NEDC. The values obtained for these coefficients are aligned with the reference one indicated by Michelin for diesel passenger cars, although these values have been found to be slightly underestimated with recent vehicle (Mallet, 2016). Once the reference pressure of 2.1 bar is defined as corresponding to the nominal rolling resistance coefficient $C_{rr,nom}$, a percentage variation of the rolling resistance coefficient can be evaluated through the LaClaire’s function (Fig.1a) for any change in the tire pressure. Therefore, the corresponding variation in fuel consumption is evaluated as:

$$\Delta fc(p_{inf})_{(U,EU)}\left[{}^{l}/_{100\ km}\right] = \alpha_{R,(U,EU)} M_{ref} \Delta C_{rr}(p_{inf}) \qquad \text{Eq.1}$$

2. The variation of fuel economy performance due to a change in vehicle mass M at the reference tire inflation pressure, evaluated through the estimation of a sensitivity coefficient α_M obtained, as for the previous case, both for urban and extra-urban driving conditions, as a linear interpolation of the average fuel consumption as a function of the vehicle mass on the reference cycles (Fig.2b):

$$\Delta fc(M)_{(U,EU)}\left[{}^{l}/_{100\ km}\right] = \alpha_{M,(U,EU)} (M - M_{ref}) C_{rr,nom} \qquad \text{Eq.2}$$

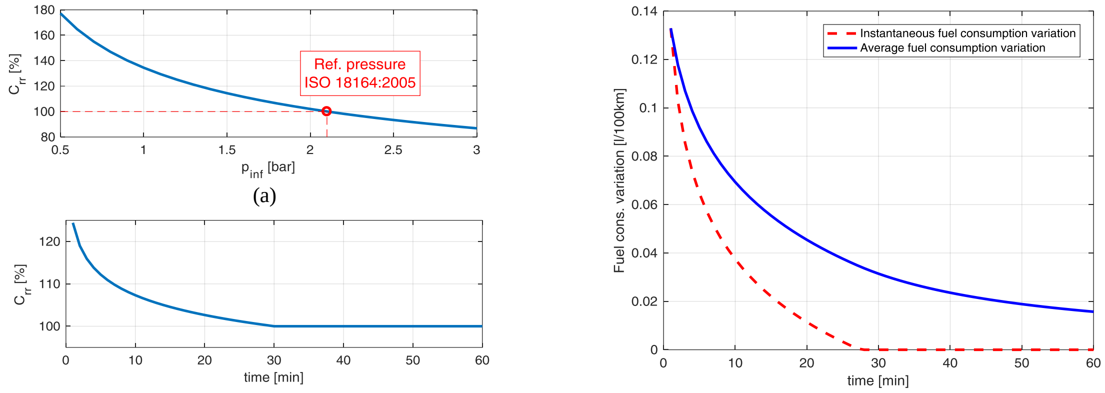
3. The variation of fuel economy performance as a function of rolling time during tire warm-up at the reference inflation and loading condition. As the rubber deformation and hysteretic properties are subject to variations during tire warm-up, the rolling resistance after a cold start is higher at the beginning and decreases in time up to reach the nominal rolling resistance as the tire reaches the steady thermal state (LaClaire, 2006). A warm-up time of 30 minutes is assumed and, as a first approximation, it is considered independent of the vehicle mission (Michelin, 2003). Therefore, referring to the graphic relation reproduced in Fig. 1b, it is possible to evaluate the variation of tire rolling resistance $\Delta C_{rr}(t_{roll})$ at a certain time instant t_{roll} after a cold start. Applying the sensitivity coefficients $\alpha_{R,U}$ and $\alpha_{R,EU}$ (cf. Fig

2a) it is then possible to obtain the corresponding instantaneous worsening in fuel consumption with respect to the nominal one, during the rolling time (red dashed curve in Fig. 1c):

$$\Delta fc(t_{roll})_{(U,EU)}\left[{}^{l}/_{100\ km}\right] = \alpha_{R,(U,EU)} M_{ref} \Delta C_{rr}(t_{roll}) \qquad \text{Eq.3}$$

The worsening $\Delta fc_{trip,CS}$ due to cold-start of the tires along the trip duration is then calculated as the temporal average over the whole trip, between the initial instant t_0 and the instant t_{eot} corresponding to the end of the trip (blue solid curve in Fig. 1c):

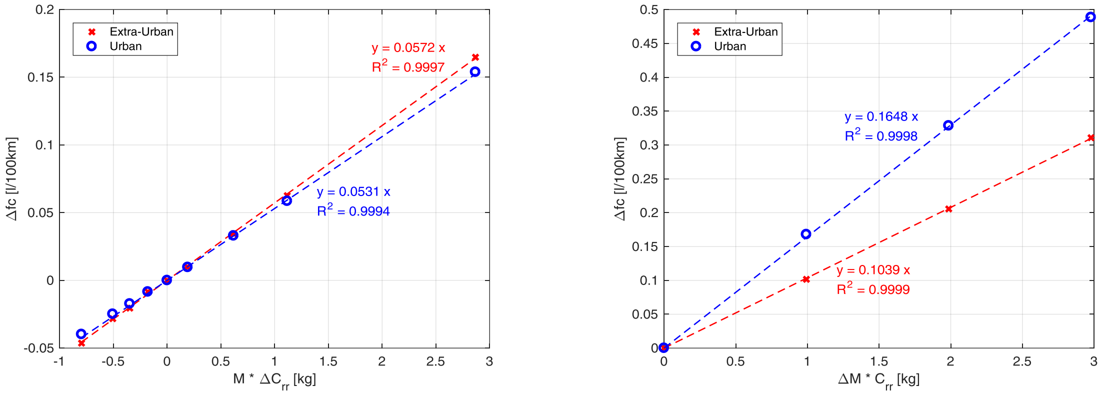
$$\Delta fc_{trip,CS}\left[{}^{l}/_{100\ km}\right] = \frac{1}{teot - t_0}\int_{t_0}^{teot} \Delta fc(t_{roll})\, dt \qquad \text{Eq.4}$$



(a)

(b) (c)

Fig.1 – Percentage variation of tire rolling resistance with inflation pressure (a) and during the tire warm-up (b); fuel consumption variation during tire warm-up: instantaneous variation in fuel consumption during a warm-up and average worsening along the trip (c).



(a) (b)

Fig.2 – Fuel consumption variations: sensitivity to rolling resistance variations (a) and sensitivity to mass variations (b)

As Δfc in Eqs. 1-3 is linearly dependent on ΔC_{rr} and ΔM and as the abovementioned effects, at least as a first approximation, are independent one of the other, the effects are combined by applying the superposition principle. In particular, the minor dependence of C_{rr} on the vertical load on the tire is neglected. Therefore, the final average fuel consumption along a trip in a generic loading condition M, with tires inflated at a certain pressure p_{inf}, where the vehicle is started with cold tires and whose time duration is $(t_{eot} - t_0)$, is calculated summing the worsening terms of Eq.1, Eq.2 and Eq.4 to the average fuel consumption in reference conditions:

$$fc_{trip}\left[{}^{l}/_{100\ km}\right] = fc_{ref} + \alpha_{R,(U,EU)} M_{ref} \Delta C_{rr}(p_{inf}) + \alpha_{M,(U,EU)}(M - M_{ref}) C_{rr,nom} + \frac{1}{t_{eot} - t_0}\int_{t_0}^{t_{eot}} \Delta fc(t_{roll})\, dt \qquad \text{Eq.5}$$

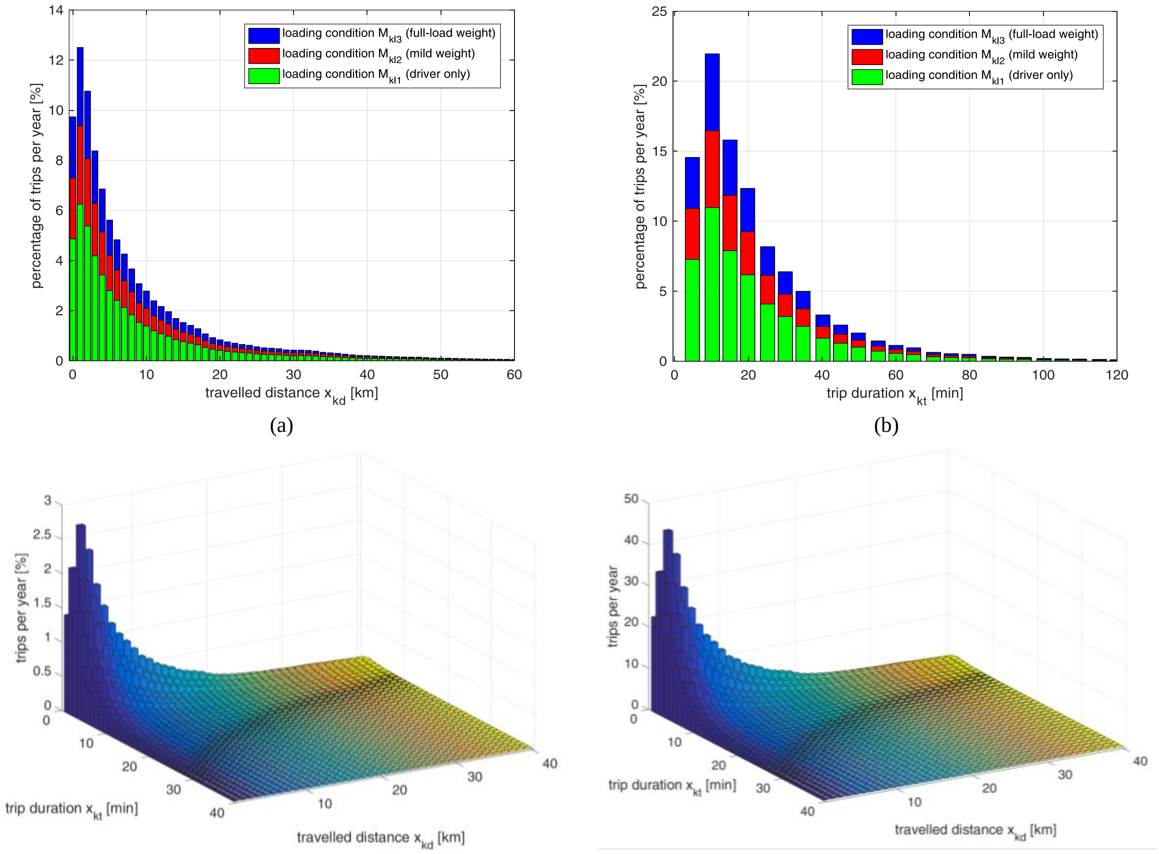
where the last term, related to tire cold-start cases, is not considered for trips that start with warm tires.

In order to refer the calculation to the annual mission of a mid-size vehicle, the following data are considered:

- 4.4 trips per day, i.e. the average daily trips in Florence, Italy (De Gennaro et al., 2014 and JRC, 2015);

- distributions of the percentage of trips f_T as a function of the travelled distance x_d and of the trip duration x_t, being x_d and x_t divided into classes k_d and k_t (Fig. 3a and 3b), respectively, obtained from the elaboration of the cumulative number of trips acquired in Florence (De Gennaro et al., 2014 and JRC, 2015).

The two distributions of the percentage of trips f_T as a function of the travelled distance x_d and of the trip duration x_t are multiplied between them in order to obtain a 3D distribution in which each element represents the percentage of trips per year whose travelled distance is within the class k_d and whose duration is within the class k_t (cfr. Fig.3c). In order to obtain the number of trips for each class combination (k_t, k_d), the obtained matrix is then multiplied by the total number of trips per year, i.e. 4.4 trips per day for 365 days. The result is shown in Fig. 3d. By summing all the contributions of each time class k_t for a single distance class k_d, and multiplying the number of trips per each class of distance k_d by the corresponding trip distance $x_{k,d}$, a distribution of kilometers per distance class is obtained. Finally, the contribution of all the distance classes, can be summed to get the total number of travelled kilometers. According to the abovementioned input data and procedure, a yearly mileage of approximatively 14'900 km/year is obtained, which is close to the average travelled distance per year per vehicle in Europe according to ACEA (2017), i.e. 13'000 km/year.
In order to take into account the effects of urban and extra-urban driving conditions on total annual fuel consumption, 55% of the annual mileage obtained from above calculations is supposed to be travelled in urban mode, and the remaining part is considered as extra-urban mileage (Pearce, 2007). The trips distribution of Fig. 3b is therefore rescaled according to the abovementioned driving mode percentages.



(a)

(b)

(c)

(d)

Fig.3 – Distributions of the percentage of trips per year as a function of the travelled distance per trip (a) and of the duration of each trip (b); percentage of trips (c) and number of trips (d) for each class of trip duration and travelled distance.

Moreover, a distribution of loading conditions M_{kl} is supposed, which considers that a fraction $f_{T,kl} = 50\%$ of the trips are travelled in the reference loading condition (driver only), $f_{T,kl} = 25\%$ of the trips in full-load weight condition, and the remaining trips are travelled in an intermediate loading condition evaluated as the average between the full-load weight and the driver-only case. Such a distribution is applied to each of the classes defined in the previous distributions (cf. Fig.3a and Fig 3b).

In case of trips with tire hot-start, for each of the three considered classes M_{kl} of mass, Eq.5 is applied (neglecting the warm-up term) to calculate average fuel consumption (in l/100km). Absolute fuel consumption (in liters) is then calculated, multiplying the corresponding average fuel consumption by the yearly travelled distance in urban and extra-urban modes and for each class M_{kl}. The contributions of the various masses and of the urban and extra-urban modes are then summed to provide the total annual fuel consumption. In formula:

$$fc_{year}[l] = \sum_{(U,EU)} \sum_{\forall k_l} \left\{ f_{T,kl} \cdot d_{(U,EU)} \cdot \frac{1}{100} \left[fc_{ref} + \Delta fc(p_{inf}) + \alpha_{M,(U,EU)} (M_{kl} - M_{ref}) C_{rr,nom} \right] \right\} \qquad \text{Eq.6}$$

being $d_{(U,EU)}$ the total yearly travelled distance in km in urban and extra-urban mode, respectively.

In case of tire cold-starts, Eq. 5 is applied, including the warm-up term, to each single class combination (k_t, k_d) of the distributions represented in Fig.3a and Fig.3b. The duration $(t_{eot} - t_0)$ of the trip in Eq.5 corresponds to the value x_{kt} representative of the corresponding class k_t. The obtained result is then multiplied by the travelled distance per trip x_{kd} representative of the class k_d to obtain a fuel consumption value $fc_{(x_{kt},x_{kd})}[l]$ representative of each trip referred to the combination (k_t, k_d). The total yearly fuel consumption is then obtained multiplying these values times the number of trips related to the corresponding combination $n_{T,(x_{kt},x_{kd})}$ and summing all these contributions. This calculation is repeated for each loading condition M_{kl} and the contributions are then summed:

$$fc_{trip,(x_{kt},x_{kd},M_{kl})} \left[\frac{l}{100km} \right] = fc_{ref} + \alpha_{R,(U,EU)} M_{ref} \Delta C_{rr}(p_{inf}) + \alpha_{M,(U,EU)} (M_{kl} - M_{ref}) C_{rr,nom} + \frac{1}{(t_{eot} - t_0)_{kt}} \int_{t_0}^{t_{eot,kt}} \Delta fc(t_{roll})\, dt \qquad \text{Eq.7}$$

$$fc_{year}[l] = \sum_{\forall (k_t,k_d)} \sum_{\forall k_l} \left[f_{T,kl} \cdot n_{T,(x_{kt},x_{kd})} \cdot \frac{1}{100} \cdot x_{kd} \cdot fc_{trip,(x_{kt},x_{kd},M_{kl})} \right] \qquad \text{Eq. 8}$$

3. Scenarios and pressure management strategies

The methodology described above has been applied considering different combinations of the effect of tire cold-starts and trips with variable loading condition. The following scenarios, relative to the vehicle utilization, have therefore been analysed:

- *scenario 0*: the annual fuel consumption is evaluated considering the annual mileage in urban and extra-urban modes. All the trips start with warm tires and at the reference loading condition (driver only).
- *scenario 1*, stemming from *scenario 0*, considers the worsening in fuel consumption (Figs. 1b and 1c), assuming that all the trips in a year are started with cold-tires. This is meant to represent a realistic daily usage of the passenger car, where the car is mainly used for commuting (tires cool-down to ambient temperature between one trip and the following one).
- *scenario 2*, based on *scenario 0* and *1*, considers that 80% of the trips start with cold tires, while the remaining ones are started with tires already at the rated temperature to take into account short stops.
- *scenario 3*, stemming from *scenario 0*, considers half of the trips in the reference condition of mass (driver only) and the remaining trips equally distributed on loading conditions with intermediate vehicle mass and with the full-load weight.
- *scenario 4* considers the effect of variable loading conditions with 100% of the trips starting with cold tires. It is the superposition of the effects considered in *scenario 1* and *scenario 3*:

  $$fc_{sc4}\left[{}^{l}/_{100\ km}\right] = fc_{ref} + \Delta fc_{sc1} + \Delta fc_{sc3} \qquad \text{Eq. 11}$$

  scenario 5 considers the effect of variable loading conditions with a percentage of the trips starting with cold tires, indicated by the symbol $\%CS$, being $\%CS$ equal to 80%. Therefore, $\%CS$ of fuel consumption calculated in *scenario 4* (variable mass, 100% cold start) is summed to (1-$\%CS$) of the contribution of *scenario 3* (variable mass, 100% hot start):

  $$fc_{sc5}\left[{}^{l}/_{100\ km}\right] = \%CS \cdot fc_{sc4} + (1 - \%CS) \cdot fc_{sc3} \qquad \text{Eq. 12}$$

For each of these scenarios, different pressure management situations have been considered:

- *reference*: tires are always inflated at the nominal pressure indicated by the vehicle manufacturer for the driver-only case. Therefore, this case is representative of a driver which properly maintains the tires, or to the usage of an on-board system able to keep always a reference pressure (but not able to adapt the pressure to the vehicle working conditions). The reference tire pressure considered is 2.1 bar.

- *misuse 75%*: tires are always inflated at 75% of the reference pressure. This corresponds to improper tire maintenance where the tire pressure is, in average along the year, 25% lower than the nominal one. Considering a natural decrease of tire pressure of 0.1 bar per month, this misuse condition corresponds to checking tire pressure two times per year.
- *misuse 85%*: tires are always inflated at 85% of the reference pressure. This corresponds to a case of improper tire maintenance, but less critical than the one described above, e.g. with a lower natural deflation rate or checking the tires more often.
- *strategy 1*: it is considered that an automatic system is installed on-board (Vitolo et al., 2015). Pressure is adapted to load variations in order to maintain always the same static tire radius. Moreover, an initial small over-inflation is realized for the trips which are started with cold tires, and then some air is gradually released as the tire temperature increases, according to an isobaric transformation.
- *strategy 2*: based on *strategy 1*, considers an additional pressure management strategy which slightly increases tire pressure in extra-urban conditions.

As a reference, an example of a system able to vary tire pressure automatically on-board is reported in Figure 4. The presented system has been developed and prototyped at the Politecnico di Torino and is specifically designed to fit on a passenger vehicle (Vitolo et al., 2015). The system is composed by a central part installed on the chassis and comprising a compressor and a vacuum generator (both included in item 1 of Fig. 4) and a group of line control valves (items 2, 3, 7 and 8), and a terminal part installed on the wheel including a system of valves set to isolate the tire from the rest of the system when the system is not actuated (valve block 4 in Fig. 4). The on-rim valve block 4 also limits the minimum tire pressure that can be realized through a deflation operation. The central part on the chassis and the terminal part installed on the rim are fluidly connected via pneumatic rotating joints (items 6), which will have different shapes and characteristics according to the specific wheel/suspension architecture. A relief valve (item 5) is included for safety reasons to limit the maximum tire pressure in the system. Wired pressure transducers placed along the pipes are used to measure tire pressure when the valves in the rim-mounted block 4 are open for pneumatic communication: the pressure measured along the line is correlated to in-tire pressure through an experimental correlation function that takes into account of the pressure drops along the line.

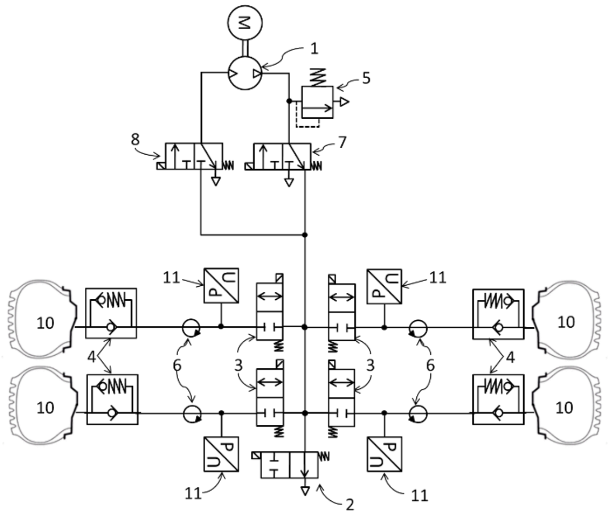


Fig.4 – Schematic of the automatic central tire inflation pressure system developed at the Politecnico di Torino for passenger cars.

4. Single vehicle analysis: results and discussion

With reference to Fig. 5, the results of this analysis concerning a single vehicle are reported in terms of relative variations in fuel consumption and increase of annual CO_2 emissions. More in detail, Fig. 5a shows a comparison among the *reference* cases calculated for the various *scenarios*, i.e. highlights the effect of considering different loading conditions as well as of tire cold-starts keeping always the nominal tire inflation pressure. Loading conditions different from the reference one (curb weight + driver) contribute to increase real-world fuel consumption with respect to type-approval procedures. Additionally, Fig. 5b reports, for each *scenario*, the variations obtained due to improper or advanced tire pressure management with respect to the *reference* case.

As previously stated, *scenario 0* represents the condition with tires always at the rated temperature and vehicle at the reference loading condition. Since all the trips are at reference load and temperature, *strategy 1* has no effect and *strategy 2* has a minor improvement (-0.3%) due to the variation of pressure only on extra-urban driving conditions.

Comparing the *reference* case in *scenario 0* with those in *scenario 1* and *2*, the consequence of introducing in the calculation the effect of tire cold-starts is highlighted (Fig. 5a). This corresponds to an increase of about 1% in fuel consumption, 8.4-6.7 litres of fuel and 22.3-17.8 kg of CO_2 per year per vehicle, considering 100% and 80% of the trips starting with cold-tires, respectively. Referring to *scenario 2* (80% cold-start), *misuse 75%* and *misuse 85%* increase fuel consumption by 1.43%-0.79% (up to 28.5 kg of CO_2), respectively, if compared to *reference* case of the same scenario (Fig. 5b). On the other hand, still referring to *scenario 2*, the proposed strategies reduce fuel consumption up to 0.8% with respect to *reference*, allowing to save up to 16.3 kg of CO_2 emissions.

The *reference* case of *scenario 3* shows that real-world operating loading conditions, not considered by current type-approval procedures, account for an increase of 3% of fuel consumption (59 kg of CO_2, cf. Fig. 5a). The *misuse 75%* case determines a worsening in fuel consumption of about 1.4%, as for the previous scenarios. On the other hand, pressure management strategies allow improving fuel economy up to 0.9% with respect to the *reference* case.

Scenario 4 and *5* show a linear combination of the cold-start and of the operating mass effects. Referring to *scenario 5*, the two considered effects account for an increase up to 3.9% of real-world fuel consumption (77 kg of CO_2, cf. Fig. 5a) – with respect to *scenario 0* – if the nominal pressure is maintained in all the trips (*reference* case). Misuse further increases fuel consumption by 1.4% and up to 28 kg of CO_2 per year (*misuse 75%* with respect to *reference* case of *scenario 5*, cf. Fig. 5b). Proposed pressure management strategies can reduce fuel consumption of about 1-1.4% (*strategy 1* and *strategy 2*, respectively) if compared to the *reference* in *scenario 5*, with a reduction of 20-29 kg of CO_2 per year (Fig. 5b). Still with reference to *scenario 5*, considering *misuse 75%* as representative of the average current driving condition in Europe and *strategy 2* as the best case obtainable through an active tire management, the maximum potentiality of the studied technology on the reference car is about 2.8% on the reduction in fuel consumption and 58 kg of CO_2.

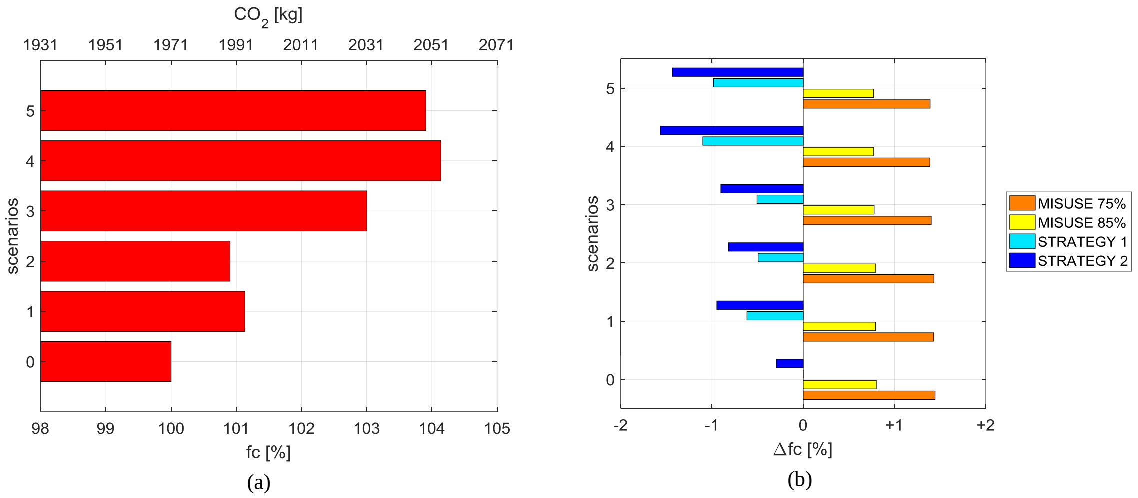


Fig.5 – CO_2 emissions and percentage variation of fuel consumption comparing the *reference* cases of the various considered *scenarios* (a); percentage variation of fuel consumption on misuse cases and pressure management strategies with respect to the *reference* case on each of the considered *scenarios* (b).

5. Impact assessment on European scale

Moving from the results obtained for a single vehicle, for each of the considered scenarios and strategies, the total effect on CO_2 emissions in Europe and the related Social Cost of Carbon (SCC) have been calculated (EPA, 2016), considering 256 million vehicles that correspond to all the European fleet of passenger cars (ACEA, 2017). Results are based on the hypothesis that all the European circulating fleet has the same fuel economy figures as the reference vehicle, which is mid-size 2010 passenger car. Anyway, the circulating fleet is more heterogeneous and with an average vehicle age of 10 years (ACEA, 2017), which determines an underestimation of the global effects. The SCC metric is a valuable way to quantify, in current monetary value, the long-term effect of CO_2 emissions. Since SCC is strongly sensitive to the discount rate, i.e. to the present value of future damages, and due to the uncertainties associated to this kind of estimation, instead of using a single figure, three different discount rates are used to provide a possible variation range of the costs/benefits value. Therefore three different integrated assessment models are applied (5%, 3% and 2.5% discount rates). For each of the models, the US EPA indicates as reference carbon price the average of the three frequency distributions, which corresponds to assume an average damage scenario. Moreover, considering that greenhouse gases emissions may produce negative effects higher than the potential damage that can be quantified nowadays, the 95th percentile of the distribution obtained at 3% discount rate is also considered. Although these models do not include all the damages produced by carbon emissions, however these are effective in case of cost-benefits analysis or in case of a comparison among different technologies devoted to the reduction of greenhouse gases emissions. The SCC figures have been estimated in

2007 US dollars and reported in euros according to the current rate of change, equal to 1.1988 $/€ (September 2017).

If *scenario 5* is taken into account, therefore considering the effect of tire pressure management under the hypothesis that 80% of the trips start with cold tires and in various loading conditions, common underinflation (*misuse 75%* and *misuse 85%* compared to *reference*) causes the waste of 10 to 17 million barrels of fuel (1'500'000 to 2'700'000 m^3) and the emission of 4'040'000 to 7'290'000 metric tons of CO_2 every year in Europe. Considering that the transportation sector correspond to 6.86 $GtCO_2eq$/year, i.e. 14% of the total anthropogenic greenhouse gases emissions (IPCC, 2014), tire underinflation accounts, therefore, for 0.06% to 0.1% of the total. According to the estimations of the social cost of carbon provided by US EPA (2016), the economic value of this yearly increase in CO_2 emissions will be 73 to 377 million € in 2020 (*misuse 75%*), depending on the average discount rate considered for the integrated assessment models used for the SCC analysis (5 to 2.5%), and up to 748 million € considering 95th percentile SCC estimate according to a 3% discount rate. Since the SCC increases over time to take into account of the increased incremental damage, if no action is taken to reduce tire underinflation – and supposing that the possible increase in the number of circulating vehicles in the coming decades will be compensated by fuel economy improvements – the same amount of emissions in 2050 would cost 158 to 578 million € (5 to 2.5% discount rate), up to 1'289 million € (3% discount rate, 95th percentile). On the other hand if the application of an active tire pressure control system is taken into account (*strategy 2* compared to *reference*, *scenario 5*), it would be possible to save 17.8 million barrels of fuel (2'836'000 m^3) and 7'500'000 metric tons of CO_2 per year, that corresponds to a reduction of SCC up to 771 million € in 2020 and 1'329 million € in 2050 (3% discount rate, 95th percentile).

Moreover, referring to the in-use vehicle economy and considering an average cost of diesel on 1.154 €/l in Europe (European Environment Agency, 2017), the increase in fuel consumption due to underinflation costs in total up to 3.2 billion €/year (*misuse 75%* with respect to *reference*, *scenario 5*) to European drivers, while the reduction which could be obtained through advanced pressure management strategies would allow to save 3.3 billion €/year, with respect to *reference* case. Overall, advanced pressure management would allow to save 6.5 billion €/year with respect to a typical misuse case.

A further economic advantage could be obtained from the consequent increment in tire life. Tire durability reduction can be calculated by linearizing some figures provided by TUV (2003), which show a reduction of 10%, 25% and 45% of tire life for a tire inflation pressure respectively 0.2, 0.4 and 0.6 bar lower than the reference. Therefore *misuse 75%* and *misuse 85%* correspond to 37.5% and 18.6% tire life reduction, respectively. Considering a nominal tire life of 50'000 km (warranted mileage on the North-American market by Michelin, 2013), an annual mileage of 14'900 km and an average tire cost on the market of about 80 €, it is possible to estimate an increase of costs between 22 € and 57 € per year per vehicle, i.e. 5.6 to 14.7 billion €/year for the whole European fleet.

Additionally, 3.3% of all the crashes related to tire are due to improper inflation, which are responsible for 35 fatalities, 370 severe injuries and 3654 slight injuries per year in Europe (TREN-ECON2-002, 2006). Assuming that an active central tire inflation system may potentially avoid all the crashes due to improper tire inflation, this kind of system may generate a further economic benefit of 207,6 million €. For these quantification, the cost of personal damage, property damage and congestion caused by road crashes have been considered by updating the values reported in TREN-ECON2-002 (2006), referred to 2005, by taking into account of the current value of money with respect to 2005.

6. Conclusions

The concerns on vehicle fuel economy and safety are increasing, and tire inflation pressure affects both these crucial aspects. Therefore, a technological assessment is proposed in this work in order to provide a preliminary quantification of the socio-economical effects of tire pressure management. Although an increasing interest has been shown on the topic in recent years, the current solutions on the market (tire pressure monitoring systems) represent only a partial answer to the problem: first, since the drivers are still in charge for manually managing tire pressure, providing them the proper information does not guarantee that the pressure will be adapted on all the running fleet; second, the tire pressure cannot be adapted to vehicle working conditions; third, the measurement accuracy is generally poor. Therefore, this study focused on an assessment of the potential benefits that could be obtained through an autonomous and intelligent management of tire pressure through an automatic on-board system.

The studied technology could improve real-world fuel economy by 2.8% and reduce CO_2 emissions of 58 kg per vehicle per year (3.9 g/km in average). Referring to the whole European fleet, this corresponds to a decrease up to 6.5 billion € in costs of fuel and 1.5 billion € in social cost of carbon emissions (referred to 2020 CO_2 emissions). Moreover, it can be assumed that autonomous tire pressure management could avoid all the crashes related to improper tire management, potentially saving 35 lives and 4’000 injuries per year in Europe. This also corresponds to a reduction of costs related to personal damage, property damage and congestions by 200 million €/year. Additionally, the proposed technology could improve tire life, with a reduction of tires cost up to 14.7 billion €/year on European scale. The total economic value of the benefits provided by this kind of technology can therefore be quantified in 22.8 billion € per year, which would increase in time due to the increase in social cost of carbon. Reporting this to a single vehicle, it roughly corresponds to a benefit of 82 €/year.

Although this estimation may be affected by a number of assumptions, and considering that the core figures are based on statistical data, this result provides the order of magnitude of the potentialities of this technology. Therefore, the methodology here presented, as well as the results, can be seen as a reference for further studies on the topic, i.e. for policy-makers and investors to evaluate this option as an additional feature for tomorrow’s vehicles.

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