Diagnostics monitor of the braking efficiency in the on board diagnostics system for the motor vehicles

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Abstract. The article presents diagnostics monitor for control of the efficiency of brakes in various road conditions in cars equipped with pressure sensor in brake (ESP) system. Now the brake efficiency of the vehicles is estimated periodically in the stand conditions on the base of brake forces measurement or in the road conditions on the base of the brake deceleration. The presented method allows to complete the stand – periodical tests of the brakes by current on board diagnostics system OBD for brakes. First part of the article presents theoretical dependences between deceleration of the vehicle and brake pressure. The influence of the vehicle mass, initial speed of braking, temperature of brakes, aerodynamic drag, rolling resistance, engine resistance, state of the road surface, angle of the road sloping on the deceleration have been analysed. The manner of the appointed of these parameters has been analysed. The results of the initial investigation have been presented. At the end of the article the strategy of the estimation and signalization of the irregular value of the deceleration are presented.

1. Introduction
On board diagnostics program for the ABS/ESP system tests the state of the electronic and electric elements of this system. Mechanical and hydraulic elements are not tested, although quality of working the whole system depends on the efficiency of the electronic, as well as mechanical elements. Inspection of the mechanical elements needs to build more advanced diagnostic monitors. Example of these monitors are procedures for control of the brake lining wear and monitor of the unequal brake forces on the same axle of the vehicle [2, 4, 8].
The paper presents new diagnostics monitor for control of the efficiency of brakes in various road conditions in cars equipped with pressure sensor in brake (ESP) system. This procedure together with monitor of the unequal brake forces on the same axe of the vehicle allow to test currently these parameters which are controlled during obligatory periodical technical inspection of the vehicles on the roller stands. Presented method allows to replace or to complete the stand periodical tests by current on board diagnostics system OBD. It is the important problem for systems responsible for active safety in the road traffic.
The brake efficiency of the vehicles during periodical technical inspection is tested in the stand conditions on the base of brake forces measurement on the roller stands or in the road conditions on the base of the brake deceleration [1]. The conditions of these tests are established by special regulations [1]. The efficiency of braking tested in the stand conditions is calculated on the base of dependence:
\[ z = \frac{\sum F_h}{G_c} \cdot 100\% \]  

(1)

\[ \sum F_h \] – sum of the maximum brake forces measured on the stand,  
\[ G_c \] – vehicle total weight from vehicle total mass \(dmc\)

The efficiency of braking in the road conditions is calculated on the base of dependence:

\[ z_{dr} = \frac{b_m}{g} \cdot 100\% \]  

(2)

\[ b_m \] – mean brake deceleration, measured in road conditions,  
\[ g \] – earth acceleration, \(g=9,81\text{m/s}^2\)

The conditions of the road tests are established by regulations: the measurement of the deceleration during intensive braking on the flat surface of the road in good state, the initial speed about 30 km/h. For example, the coefficient of the brake efficiency calculated on the base of the stand or road tests for the passenger cars ought to be not less than 58% (for cars registered from 07/2010).

2. Diagnostics monitor of the brake efficiency

The state of the brakes and the conditions of braking change during car exploitation and influence on the brake efficiency. For these reasons the special procedure for on board diagnostics system has been worked. It allows to estimate if the deceleration measured in current road conditions performs the requirements of the regulations.

Dependence between vehicle deceleration and forces acting on the braked car in the longitudinal direction is following:

\[ m\ddot{x} = \sum F_{br} - \frac{\sum M_{iw}}{r_d} + F_{rol} + F_{air} + F_{eng} \pm F_{hill} \]  

(3)

where:

\[ m \] – vehicle mass,  
\[ \ddot{x} \] - vehicle deceleration,  
\[ \sum F_{br} = \sum M_{br}/r_d \] – sum of braking forces caused by the braking moments,  
\[ M_{iw} = J_k \ddot{\phi}_k = \frac{J_k}{r_t} \ddot{x} \] - inertia moment of the wheel,  
\[ F_{air} = A_c x \frac{D^2}{2} \ddot{x} \] - aerodynamic drag,  
\[ F_{rol} = G \cos \alpha \] - rolling resistance,  
\[ F_{eng} = M_{eng}/r_d \] - the engine resistance reduced to the vehicle wheels,  
\[ i \] – overall drivetrain ratio  
\[ F_{hill} = G \sin \alpha \] - the climbing resistance  
\[ G \] – vehicle weight,  
\[ \alpha \] – angle of the road slope,  
\[ r_d \] – dynamic radius of the wheel,  
\[ r_t \] – rolling radius of the wheel,
For the brakes with ABS/ESP system with pressure sensor, dependence between sum of braking forces and pressure in the hydraulic system, for the brakes without braking force regulator, can be calculated on the base of dependence:

$$\sum F_{br} = f(p) = (k_p + k_i) p$$

(4)

$p$ – pressure in the brake master cylinder,

$k_p, k_i$ – proportional coefficients for front and rear wheels calculated experimentally

Dependence (4) is actual to the moment of ABS operation and it can change with the brakes temperature and initial speed of braking. These parameters can be taken into consideration as the coefficients $k_{temp}$ and $k_v$ established experimentally:

$$\sum F_{br} = f(p) = (k_p + k_i) p \cdot k_{temp} \cdot k_v$$

(5)

On the base of equation (3) and (5) we can establish relation between deceleration of the vehicle and pressure in the brake system:

$$\ddot{x}(p) = \frac{1}{m + \sum J_k \frac{r_k}{r_i}} \cdot \left\{ (k_p + k_i) p \cdot k_{temp} \cdot k_v + mg \cos \alpha + A c_x \frac{P}{2} \dot{x}^2 \pm mg \sin \alpha + F_{eng} \right\}$$

(6)

During working out of this diagnostic monitor, the dependence between deceleration and brake pressure $\ddot{x}(p)_{dmc}$ for the vehicle with the efficient brakes, vehicle total mass $dmc$ and for the established conditions of the braking, ought to be measured, fig. 2. This characteristic ought to be written to ROM of the brake controller. It is the base for following analyses and estimations. The base characteristics ought to be made for few ranges of the initial speed of braking. The load of the vehicle changes during exploitation of the car and for the same pressure $p$ the brake deceleration depends on the current mass $m$. Quantity estimation of the brake efficiency depends on the comparison of the measured deceleration $\ddot{x}_m$ for the current mass $m$ of the vehicle to the deceleration $\ddot{x}_{dmc}$ for the $dmc$ mass and the same pressure $p$ in the hydraulic system and similar conditions of braking.

During braking the vehicle with the mass $m$ and mass $dmc$, on the road with the same hill slope and rolling resistance, the characteristic $\ddot{x}(p)_{m}$ ought to run over the characteristic $\ddot{x}(p)_{dmc}$ (fig. 2). It means that if the tested car with mass $m$ reaches deceleration $\ddot{x}_{gr}$ required by regulations, then brake pressure $p$ for this deceleration $\ddot{x}_{gr}$ ought to be less than $p_{gr}$ for $\ddot{x}_{gr}$ for mass $dmc$, fig. 2.

The value of the pressure $p_{gr}$ which causes the required deceleration $\ddot{x}_{gr}$ for the mass $dmc$ and efficient brakes ought to be established in time of the worked out of this diagnostic monitor.
During braking on the horizontal road with small rolling resistance, for the deceleration about 4 m/s$^2$ and more, the inert resistance of wheels and rolling resistance of wheels are similar and have opposite signs [9]. For these condition, the equation (3) can be described as:

$$m\ddot{x} = \sum F_{br} + F_{air} + F_{eng}$$  \hspace{1cm} (7)

The air resistance $F_{air}$ doesn’t depend from the mass of the vehicle but from the speed. For the same conditions of braking, on the base of the equations (4) and (7) can be described:

$$\ddot{x}_m(p) = \frac{1}{m}[(k_p + k_r)p + F_{air} + F_{eng,m}]$$  \hspace{1cm} (8)

and

$$\ddot{x}_{dmc}(p) = \frac{1}{dmc}[(k_p + k_r)p + F_{air} + F_{eng,dmc}]$$  \hspace{1cm} (8a)

From the equation (8) and (8a) results that during braking in the same road conditions for the same pressure $p$ and initial speed, with clutch uncoupled, the ratio of the decelerations for mass $m$ of the vehicle and mass $dmc$ ought to be:

$$\frac{\ddot{x}_m(p)}{\ddot{x}_{dmc}(p)} = \frac{dmc}{m}$$  \hspace{1cm} (9)

Because of the small difference between deceleration $\ddot{x}_m(p)$ and $\ddot{x}_{dmc}(p)$, the engine resistance values for the same transmission ratio, initial speed and clutch coupled are similar for the mass $m$ and $dmc$: $F_{eng,m} \approx F_{eng,dmc}$. For this assumption the dependence (9) is actual during braking with transmission engaged.

Above conditions oblige in the range of braking without ABS acting.

If the diagnostic program contains procedure for estimation of the current mass of the vehicle then the diagnostic monitor compares the measured deceleration $\ddot{x}_m(p)$ to the deceleration $\ddot{x}_{dmc}(p)$.

Estimation if the vehicle achieved deceleration $\ddot{x}_{gr}$ required by regulations (for example 5.8 m/s$^2$ for the passenger cars) is seldom performed during intensive braking. On the slippery roads deceleration required by regulations can be not reached. For these situations we can enlarge the evaluation of the brakes on the wide range of braking efficiency by calculation of the coefficient $\gamma$ described as:

$$\gamma = \frac{\ddot{x}_m(p)}{\ddot{x}_{dmc}(p)}$$  \hspace{1cm} (10)
\(\ddot{x}_m(p)\) - measured brake deceleration for pressure \(p\) and current mass \(m\),
\(\ddot{x}_{dmc}(p)\) - deceleration for the mass \(dmc\) and pressure \(p\) according to characteristic written in ROM

In the all range of the braking pressure, it ought to be \(\gamma > 1\) for \(m < dmc\).

### 3. Conditions of the on board diagnostics

Monitor of the brake efficiency requires particular conditions for performing the measurements. The initial investigation confirmed the necessity of the performing few conditions for the trustworthy assessment of the current measured deceleration \(\ddot{x}_m(p)\). From dependence (6) results that the brake deceleration depends from many parameters: design parameters \((J_k, r_t, m, A, c_x)\) and current conditions of braking \((\text{vehicle speed}, \text{engine resistance}, \text{brake temperature}, \text{grade of hill resistance}, \text{rolling resistance}, \text{road coefficient of friction})\). These factors ought to be taken into consideration in the diagnostic algorithm.

Construction parameters can be written to the diagnostics program as constant coefficients. External parameters ought to be analysed.

#### 3.1. Vehicle speed and deceleration

Characteristics \(\ddot{x}_{dmc}(p)\) ought to be tested and set in the program for a few values of the initial speeds of braking. Then the measured brake deceleration \(\ddot{x}_m(p)\) for the real mass ought to be compared to the characteristic \(\ddot{x}_{dmc}(p)\) for the similar initial speed.

The deceleration of the vehicle is calculated on the base of wheel rotational speed measured by ABS/ESP sensors and differentiation of that speed. Exact calculation of the vehicle speed \(\dot{x}\) requires to take into consideration the wheel slip \(s\). The vehicle speed and deceleration are:

\[
\dot{x} = \frac{\phi_k r_t}{1 - s}, \quad \ddot{x} = \frac{r_t}{1 - s} \frac{d\phi_k}{dt}
\]

\(\phi_k\) – wheel rotational speed,
\(s\) – wheel slip

The monitor of the brake efficiency will be realised for the slip range when the ABS doesn’t work. It results from the lack of dependences between pressure in master cylinder and deceleration when slip exceeds the boundary value and ABS is working. In the range of braking without ABS acting the wheel slip has small value and can be neglected. The optimal situation is if the ESP system has longitudinal deceleration sensor.

The trustworthy calculation of the mean deceleration requires appropriate long time of braking and establishing the moment of the start and end of the calculation [6]. During breaking up to stop, the start of calculation is in the moment when the speed of the vehicle is 0.8 of the initial speed of braking and the end is when the car speed is 0.2 of the beginning speed of braking. The investigation shows that the calculation \(\ddot{x}_m(p)\) ought to be performed for initial speed of the car and braking pressure bigger than minimum values. For the tested car it was: \(\ddot{x}_{\text{min}} = 2 m/s^2, p_{\text{min}} = 20\text{bar}\). For the less values disturbances caused the excessive scatter of results.

#### 3.2. Engine resistance and rolling resistance

Engine resistance has real influence on the brake deceleration and ought to be taken into consideration in the diagnostic algorithm. The base characteristics \(\ddot{x}_{dmc}(p)\) ought to be made for the transmission ratios, bigger then 1. Measured deceleration for the mass \(m\) will be compared to the deceleration \(\ddot{x}_{dmc}(p)\) for the same transmission ratio.

The influence of the rolling resistance on the road in the good technical state is minimal in relation to the disperse of the results of measuring of the deceleration and can be neglected. Bad state of road can be recognized using the sensor of the vibrations of the car body or by analysis of unequal wheel speed as in the OBB system [7]. If the level of vibrations established in the program is exceeded, the monitor isn’t realised. Also when the tire pressure is too small the monitor isn’t realised.
3.3. Brakes temperature
This parameter isn’t measured in the on board diagnostics system. It can be taken into consideration indirectly. If the successive intensive braking are one after second in the short time period, then the result of next deceleration isn’t analysed. It is necessary to pay attention that efficiency of the heated brakes also ought to be sufficient. In connection to it if the efficiency of the heated brakes reduces under required value, then the driver ought to be informed about this situation, although the formal conditions of the test are not in accordance with the proper regulations.

3.4. Vehicle mass
The mass of the vehicle can be identified by measuring the suspension deflection or the pressure in the pneumatic suspension of the vehicle. The point of dynamic method is that the deceleration measured during overrun strip with power transmission engaged for the current mass of the vehicle is compared with the deceleration for the overrun strip for the \textit{dmc} mass and the same transmission ratio. If these measurements will be realised in the same road conditions and speed, then on the base of the dependence (8) and (8a) is:

\[ m \ddot{x}_m = F_{air} + F_{eng,m} \]

and

\[ m_{dmc} \ddot{x}_{dmc} = F_{air} + F_{eng,dmc} \]

After side subtraction of these equations the mass \( m \) can be calculated:

\[ m = \frac{m_{dmc} \ddot{x}_{dmc} + \Delta F_{eng}}{\ddot{x}_m} \]

Value \( \Delta F_{eng} \) is connected with difference between engine moment of inertia for decelerations \( \ddot{x}_m \) and \( \ddot{x}_{dmc} \). It can be estimated during working out of the program or neglected. If it is neglected, then the equation (13) can be described as:

\[ m = m_{dmc} \frac{\ddot{x}_{dmc,eng}}{\ddot{x}_{m,eng}} \]

The values of the deceleration \( \ddot{x}_{dmc,eng} \) for mass \( dmc \), transmission ratios higher than 1 and for a few speeds of the car ought to be measured and written to the diagnostic program. Deceleration \( \ddot{x}_{m,eng} \) is measured currently during driving. Calculations of the mean value of deceleration ought to be realised many times during driving. If that algorithm will be introduced to diagnostics program, the analyse of the braking efficiency may be extended on the wide range of decelerations.

3.5. Angle of the road sloping
During upgrade braking (\( \alpha > 0 \)) the deceleration \( \ddot{x}(p) \) and the brake efficiency \( z_{br}(p) \) will be bigger than on the horizontal surface for the same pressure \( p \), fig. 3. During braking on the slope surface (\( \alpha < 0 \)) the deceleration \( \ddot{x}(p) \) will be less and the estimation of the efficiency can be negative, despite of the correct state of brakes. Diagnostics program ought to distinguish these situations. For the estimation of the slope resistance we can use the inertial sensor of the longitudinal acceleration used in the hill holder system, programmed for the measurement angle of road sloping. The second possibility is calculation on the base of the difference between the deceleration during overrun strip on the horizontal road (written in the diagnostic program) and on the road before current braking.
3.6. Conditions of the road surface

Road conditions have decisive influence on the maximum brake deceleration. On the slippery surfaces deceleration doesn’t achieve the value required by regulations. Protection against the improper estimation of the brakes is control if ABS is in action in time of braking. If the ABS system operates before the achievement of the boundary deceleration \( \ddot{x}_b(p) \), then this measurement isn’t taken into consideration to brake efficiency estimation. For conditions of braking on the slippery surface or during gentle braking, the coefficient \( \gamma \) can be calculated according to dependence (10). That coefficient ought to satisfy the condition \( \gamma > 1 \) which obliges in all range of the decelerations.

Irregularities of the road surface influence on the changes of the wheel speed measured by ABS sensors and next on the calculation of the deceleration. The course of the wheel speed ought to be filtered before differentiate [5].

4. Results of the investigation

Fig. 4 presents the results of the brake deceleration measurements as the function of the brake pressure for the passenger car with mass \( m_1 = 1585 \) kg and \( m_2 = 1910 \) kg. The tests were performed on the horizontal, dry asphalt road, with clutch uncoupled, for the initial speed 50 – 60 km/h. The results were approximated by linear function. The ratio \( m_1/m_2 \) was 0.83, the ratio \( \ddot{x}_{m2}/\ddot{x}_{m1} \) was 0.81. That difference results from the spread (scatter) of the deceleration value about ±0,5 m/s² for the same brake pressure in current conditions of braking. This fact ought to be taken into consideration for determination of the conditions and criterion of the brake efficiency estimation.
On the base of the equation (9) for the pressure \( p \) and braking on the horizontal surface, the deceleration of the vehicle with mass \( m \) ought to reach value:

\[
\ddot{x}_m(p) \geq \ddot{x}_{dmc}(p) \frac{dm_c}{m}
\]  

(15)

For example, for the results presented in fig. 4 the deceleration for pressure \( p=50 \) bar and mass \( m_1 \) calculated form dependence (15) as \( \ddot{x}_{m_1} = \ddot{x}_{m_2} \cdot \frac{m_2}{m_1} \) is 6,2 m/s\(^2\). Measured deceleration for mass \( m_1 \) was \( \ddot{x}_{m_1} = 6,4 \pm 0,5 \) m/s\(^2\).

The braking efficiency \( z \), according to dependence (2), for the vehicle with mass \( m \) ought to be:

\[
z_m(p) \geq z_{dmc}(p) \frac{dm_c}{m}
\]  

(16)

Braking efficiency for mass \( m_1 \) calculated from the dependence (16) is 63\% and calculated on the base of the measurements and dependence (2) was 65\%±5\%.

Coefficient \( \gamma \) as \( \gamma = \ddot{x}_{m_1}(p) / \ddot{x}_{m_2}(p) \) was 1,24.

The measurements and calculations have shown the efficiency of the brake system.

**Estimation of the vehicle mass on the base of overrun strip**

Measurements were made for the car with mass \( m_1=1585 \) kg and mass \( m_2=1910 \) kg, with engine 1,9 TDI, with transmission ratio 2 and initial speed 50 km/h. For 5 repeats, the mean value of the deceleration for mass \( m_1 \) was 0,85 m/s\(^2\), for mass \( m_2 \) was 0,72 m/s\(^2\). Standard deviation was 0,035 m/s\(^2\). For these values the mass \( m_1 \) calculated from the dependence (14) was 1618 kg±14 kg. Real mass was 1585 kg. It means that the percentage error was 2\%. Because of scatter of the measurements, the value of the mass ought to be calculated as the mean value of the minimum 5 measurements of the deceleration. Fig. 5 shows the example of the deceleration during overrun strip with power transmission engaged for mass \( m_1 \) and mass \( m_2 \).
Figure 5. Example of the car deceleration during overrun strip with power transmission engaged for mass \( m_1 = 1585 \) kg and \( m_2 = 1910 \) kg. Engine 1.9 TDI.

5. Signalling of the braking efficiency state
Failure of the brake system the driver can notice immediately by identification of big reduction of the brake deceleration without additional signals from the on board diagnostics system. However progressive, by steps, wear of the brakes causes the reduction of deceleration in the long period and these changes can be unnoticed. For that growing inefficiency the special strategy of the estimation and signalization of the boundary state of the diagnostics parameters ought to be adapted. The statistical analysis or moving weighted mean value can be used.

5.1. Statistical analysis
For the \( n \) realized measurements of the deceleration \( \ddot{x}_m(p) \) and calculations of the coefficient \( \gamma \), the probability \( P \) that brake system doesn’t perform the condition of efficiency (\( \gamma < \gamma_{gr} \)) is calculated as:

\[
P(\gamma < \gamma_{gr}) = \frac{n_i}{n} \%
\]

(17)

\( n_i \) – quantity successive measurements for which is \( \gamma < \gamma_{gr} \)
\( \gamma \) – value of current coefficient \( \gamma = \ddot{x}_m / \ddot{x}_{dmc} \)
\( \gamma_{gr} \) – boundary value of coefficient \( \gamma \) for mass \( m \), \( \gamma_{gr} = \frac{dmc}{m} \)
If \( P(\gamma < \gamma_{gr}) \geq P_{gr} \) then the driver is informed that braking system is inefficient.
Small boundary of probability \( P_{gr} \) is profitable for safety but can cause faults type \( \alpha \) - false alarm.
Acceptation of more value boundary probability \( P_{gr} \) causes that estimation of the state of brakes will be with the bigger certainty, but can cause too late signalization of the state of inefficiency.

5.2. Moving weighted mean value
Wear of brake system in the long time, by steps, causes that in the successive braking the state of this system can changes form an efficient to inefficient and on the contrary. It is profitable for these systems to take the strategy of estimation of the moving weighted mean value [7]:

\[
\ddot{x}_n = \ddot{x}_n \cdot w + \ddot{x}_{n-1} (1 - w)
\]

(18)
or

\[
\gamma_n = \gamma_n \cdot w + \gamma_{n-1} (1 - w)
\]

(19)

\( \ddot{x}_n \), \( \gamma_n \) – value of the deceleration or coefficient \( \gamma \) in the \( n \) current measurement,
\( \ddot{x}_{n-1} \), \( \gamma_{n-1} \) – mean value of the deceleration or coefficient \( \gamma \) from \( n \)-1 previous measurements
\( w \) - the weight of the current measurement, assumed value
When the vehicle started the tour after parking, the value of the mean deceleration from the last driving cycle is accepted. Then it is compared to the first measurement in current driving cycle. Next the process of the calculation is repeated. Signaling of the incorrect state of brakes follows if the mean value of deceleration is less than boundary value: 

$\bar{x}_n < \bar{x}_{gr}$ or $\bar{y}_n < y_{gr}$

6. Conclusions

Presented algorithm of the vehicle deceleration calculation requires to store in the controller memory the maps of the deceleration value in dependence of the brake pressure, initial speed of braking and engine resistance for $dmc$ mass. This algorithm allows to calculate and estimate the deceleration for vehicles with pressure sensor in ESP system without assembling additional sensors. Proposed diagnostic monitor allows to extend the range of the on board diagnostics of brakes on the important parameter of the efficiency of brakes. It is the conditional monitor. It means that it requires to perform the following basic conditions:
- start of the braking,
- exceed the minimum initial speed and deceleration of brake,
- the braking during the longitudinal direction of movement and without ABS acting,
- braking on the good state of the road surface,
- determined time of braking

On the base of the presented conditions the program for the braking efficiency evaluation acting in the on board diagnostic system can be worked out.

Presented diagnostics monitor of the brake efficiency together with the monitor of the unequal brake forces control [4] complete the obligatory periodical technical inspection of the vehicles. In the future the on board diagnostics system OBD-Brakes can replace the system of the stand periodical tests of the brake forces.

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