Measurement analysis of braking forces and braking coefficient at different loads of a passenger vehicle

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Abstract. This paper presented an analysis of the braking force efficiency, i.e. its intensity in the case. It presented an analysis of the efficiency of braking forces, i.e. their intensity in the case when the load of a passenger vehicle was gradually changing. The change in the load of the vehicle was done by varying the number of passengers in it from one to five which is a feature of a higher number of M1 category vehicle. By increasing in the number of passengers the weight of the vehicle varied by approximately 75kg per passenger. The experimental test was performed in the technical inspection station, i.e. on standard rollers for the brake system testing. The test results shown that the relative difference of braking forces occurred on the front axle during intensive braking and that the braking coefficient was the lowest of about 69.94% in the case when only the driver was in the vehicle. It increased with increasing load, i.e. the number of passengers in the vehicle up to 85.91% and then dropped by increasing the rear passenger behind the driver and front passenger to 80.43% which can affect the stability of the vehicle when braking in the event of a dangerous traffic situation.

1. Introduction
The process of motor vehicle braking has been a preoccupation of scientific circles in the automotive industry and beyond for a long time and accordingly it emphasizes that the greatest interest has been expressed in motor vehicle braking systems. Taking into account only the information and analysis of statistical indicators a wrong conclusion can be made which means that the technical malfunction of the vehicle contributes a small percentage (4-6%) to the immediate occurrence of traffic accidents [1].

However, it should be emphasized that these statistical indicators have been having low values due to the fact that they were very difficult to identify during the analysis of the cause of the accident compared to the obvious ones (such as damaged tire, brake system malfunction, steering system malfunction, etc.). Following research into the causes of accidents Volvo company conducted certain tests immediately after the accident asking whether there was a loss of stability and handling of the vehicle involved in the accident immediately before the accident or there was another factor [2]. After the analysis of traffic accidents it was found that more than 50% of vehicles performed braking immediately before the accident, 14% lost stability due to vehicle skidding, 16% of vehicles that did not
brake lost stability in another way. Such an analysis requires a more rigorous approach to the control of the technical correctness of motor vehicles in both regular and extraordinary technical inspections. When performing a technical inspection special attention should be paid to the inspection of brake systems.

Unfortunately, nowadays given that there were a lot of competition at technical inspection stations, the quality of the detailed approach to performing technical inspection tests has been at a very low level so that sometimes completely defective vehicles receive a certificate of technical correctness and readiness for its operation and that endangers the safety of traffic on the roads. International regulations that are directly related to the issue of braking to the greatest extent derive from the ECE R13 Regulation [3]. In a large number of traffic accidents with fatal consequences for both drivers and passengers that occur in Bosnia and Herzegovina but also in the wider region, the cause of their occurrence was the loss of stability of the vehicle during braking, the research of which has been actual on a daily basis [6]. In addition to the braking force, the braking coefficient has been taken as a key factor. In previous research, the determination of the braking coefficient was performed in the phases of pressure on the brake pedal for three different braking modes, i.e.: sudden braking, gradual one and braking, where it was shown that the best efficiency of braking forces was achieved with sudden braking [4]. Also, according to similar studies, a study was conducted in order to examine the braking coefficient of a set of vehicles (tractor trailer+semi-trailer) when changing the load distribution on a semi-trailer and finding the best load distribution to achieve the highest braking coefficient [5].

The research of improving the vehicle braking coefficient was performed on the basis of the change in the diameter of the hydraulic brake hoses [7]. In this paper, the efficiency of braking force in a classic passenger motor vehicle was tested with a variation in the number of passengers from 1 to 5 with a standard weight of 75 kg.

2. Braking coefficient testing methodology

2.1. Force and moments on the braked wheel

As the total moment of inertia was reduced to the dynamic radius of the braked wheel $r_d$, it was necessary to perform an analysis of the forces and moments on the braked wheel. The analysis was performed on the example of brakes with friction discs and a hydraulic brake mechanism possessed by the ABS system. During braking, friction forces appeared between the tire and the ground. Braking was achieved when a moment was brought to the point of the vehicle in the opposite direction of its movement, and this was achieved precisely by pressing the brake pad on the brake disc. This creates a braking torque $M_k$ that opposed the movement of the wheels as shown in Figure 1.

![Figure 1. Forces and moments on the braked wheel](image-url)
During intensive braking, i.e. the pressure of the pedal by the driver of the vehicle caused the brake linings or brake pads to stick to the brake disc, as a result of which a braking moment $M_k$ occurred which created a tangential force $\vec{X}_k$ of the ground opposite to the direction of movement of the vehicle or opposite to the speed vector $\vec{v}$. In addition to this braking torque, the wheel is also affected by the rolling moment $M_f$ which also helps to stop the vehicle. In the case of a drive wheel the rolling moment $M_o$ obtained from the engine via the half-axle was calculated according to the form

$$M_o = \sum j \frac{d\omega_o}{dt} - M_{rt}.$$  \hspace{1cm} (1)

Where there was:

- $\sum j \frac{d\omega_o}{dt}$ moment of inertia of all rotating parts connected to the wheel axle,
- $M_{rt}$ reduced moment due to friction in the transmission mechanism.

2.2. Braking force efficiency test method

The experimental part of determining the intensity of braking forces as well as their efficiency was performed in an authorised vehicle technical inspection station, on a line owned by MAHA EUROSYSTEM for testing the technical correctness of vehicles with standard brake rollers. The test vehicle was a passenger motor vehicle of the SEAT brand, the technical characteristics of which were given in Table 1.

Table 1. Technical characteristics of the test vehicle

| Manufacturer     | SEAT, S.A.          |
|------------------|---------------------|
| Category         | M1 - Passenger car  |
| Brand            | SEAT                |
| Typ              | NH                  |
| Model            | TOLEDO              |
| Body type        | Hatchback           |
| The year of production | 2017            |
| Power (kW)       | 66                  |
| Engine displacement (cm³) | 1197             |
| Top speed (km/h) | 186                 |
| Acceleration from 0-80 (km/h) | 7.3               |
| Acceleration from (km/h) | 11.3             |
| Fuel Type        | Petrol (Gasoline)   |
| Emission standard | EURO 6              |
| Doors            | 5                   |
| Kerb Weight (kg) | 1081                |
| Seats            | 5                   |
| Length (mm)      | 4482                |
| Width (mm)       | 1715                |
| Height (mm)      | 1466                |
| Wheelbase (mm)   | 2602                |
| Front overhang (mm) | 876                |
| Rear overhang (mm) | 1004              |
| Front track (mm) | 1463                |
| Rear track       | 1500                |
| Number of Gears  | Manual / 5+1        |
| Drive wheel      | Front wheel drive   |
| Tires size       | 185/60R15 84 H      |
| Turning radius (m) | 10,2              |
The brake force test was performed in five cases taking into account the masses of vehicles and passengers:

I - vehicle + driver,
II - vehicle + driver + co-driver,
III - vehicle + driver + co-driver + right rear passenger,
IV - vehicle + driver + co-driver + right and middle rear passenger,
V - vehicle + driver + co-driver + right, middle and left rear passenger.

2.3. Results of brake force intensity testing and analysis of results

2.3.1. Results of tested vehicle with a driver

Figure 2 shows the results of the brake force test when there was only a driver with an approximate mass of about 75 kg in the vehicle.

In the first test, when only the driver was in the vehicle, an increased difference in braking force intensity was seen on the front axle wheels, which can be seen in the diagram when the maximum braking force approached the limit line, while the difference in braking forces on the rear axle wheels was significantly smaller.

2.3.2. Test results on the vehicle with driver and co-driver

Figure 3 shows the test results of the braking forces when the driver and co-driver were in the vehicle, i.e. when there was a slow increase in the total mass of the vehicle, which was distributed on the axles and wheels.

Figure 2. Test results (vehicle + driver)

Figure 3. Test results (vehicle + driver + co-driver)
In the second test, when the driver and co-driver were in the vehicle, an increase in the braking forces was seen on both axles, i.e. on the front and rear, but their difference also increased.

2.3.3. Test results on a vehicle with driver, co-driver and right back passenger
Figure 4. shows the test results of the braking force when the driver, co-driver and right rear passenger were in the vehicle, i.e. when there was a slow increase in the total mass of the vehicle which was distributed on the axles and wheels.

Figure 4. Test results (vehicle + driver + co-driver + right rear passenger)

In the third test when the driver, co-driver and right rear passenger were in the vehicle an increase in braking forces on the rear axle was visible, while their differences on the wheels of the same axle were significantly reduced as a result of changing the position of the vehicle centre.

2.3.4. Test results on a vehicle with driver, co-driver, right and middle rear passenger
Figure 5. shows the results of testing the braking forces when in the vehicle there were: driver, co-driver, right and middle rear passenger, or when there was a slow increase in the total mass of the vehicle which was distributed on the axles and wheels.

Figure 5. Test results (vehicle + driver + co-driver + right and middle rear passenger)

In the fourth test when the driver, co-driver, right and middle rear passenger were in the vehicle, an increase in the braking forces on the rear axle and their smaller differences on the wheels of the same axle was visible.

2.3.5. Test results on a vehicle with driver, co-driver, right, middle and left rear passenger
Figure 6. shows the results of testing the braking forces when in the vehicle there were: driver, front passenger, right, middle and left rear passenger, or when there was a slow increase in the total mass of the vehicle which was distributed on the axles and wheels.
Figure 6. Test results (vehicle + driver co-driver + right, middle and rear passenger)

In the fifth test when the driver, co-driver, right, middle and left rear passenger were in the vehicle, a decrease in the intensity of the braking forces of the front axle wheels and an increase in braking forces with a more intense difference on the front axle wheels were visible.

2.3.6. Analysis of the obtained results

It has been known that the quality of the braking system was measured by the braking coefficient prescribed by law for certain categories of vehicles, which in the ideal case is to be calculated according to the expression

\[
 z = \frac{\sum_{i=1}^{4} F_{ki}}{\left(\sum_{i=1}^{4} m_i\right) \cdot g} \cdot 100\% ,
\]

(2)

where there was:

- \(\sum_{i=1}^{4} F_{ki}\) total braking force on all wheels,
- \(\sum_{i=1}^{4} m_i \cdot g\) the total weight of the vehicle which was equal to the sum of all normal reactions on the braked wheels [8].

For the given test results in the developed form of expression (2)

\[
z_n = \frac{F_{kn}^{pl} + F_{kn}^{pd} + F_{kn}^{zd} + F_{kn}^{zd}}{\left(m_n^{pl} + m_n^{pd} + m_n^{zd} + m_n^{zd}\right) \cdot g} \cdot 100\% .
\]

(3)

Based on the expression (3) the braking coefficients were obtained:

- \(z_I = 69.94\%\)
- \(z_{II} = 84.25\%\)
- \(z_{III} = 85.97\%\)
- \(z_{IV} = 85.91\%\)
- \(z_V = 80.43\%\)
The obtained results of braking coefficients were shown by the diagram in Figure 7.

Figure 7. Diagram of the braking coefficient of the experimental values

Figure 7. shown that the braking coefficient of the test vehicle was above the minimum legally allowed 50% because it was a relatively newer vehicle that had less time in technical operation [8]. What was characteristic was the fact that the braking coefficient was changed with the change of the total mass of the vehicle and the distribution of these masses in the vehicle, as in this case the passengers.

3. Conclusion
The braking force test was performed in five cases, i.e. by gradually increasing the total mass of a passenger motor vehicle of category M1 by the mass of one passenger with an approximate mass of 75 kg. The experiment showed the deviations of the partial braking forces of individual axles and thus the deviation of the braking coefficient which was the basic technical characteristic of the quality of the vehicle brake mechanism. The test vehicle was relatively newer so that the differences in the intensity of the braking forces of the front and rear axles remained below the legal maximum 25% and the braking coefficient above the legal 50% for a given vehicle category [8]. However, as the experiment showed deviations of both parameters with increasing vehicle weight and mass position on the vehicle itself which caused a change in the centre of gravity of the vehicle, i.e. its inertial center of mass, it was very important to consider the actual schedule of passengers. other masses that were at a given moment just before its formation in order to adequately arrive at its cause.
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