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COMPARATIVE STUDY ON THE DYNAMIC BEHAVIOUR IN CORNERING FROM DIFFERENT CLASSES OF PASSENGER CARS, BY EXPERIMENTAL AND SIMULATION METHODS

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Abstract: *This paper presents a study by experimental and simulation methods on the behaviour of different classes of passenger cars in cornering, this being a common situation for their control loss and occurrence of the road accidents. The study also attempts to provide a clearer picture on the modification of the manoeuvrability degree of the passenger cars for different loads. The different states of the rolling track surface determine the variation of the friction coefficient that do not only change the limit at which the skidding occurs, but also the behaviour of the car until it has reached this limit. Within the experimental determinations, the parameter values were chosen so as to characterize the real situations frequently encountered in the cornering process, considering the factors that influencing their movement and tendency of the cars in cornering. The computer simulations, highlights the evaluation of the parameters whose variation determines a change of the manoeuvrability degree for the passenger cars. The results, from the experimental methods and computer simulation have graphics interpretation, enabling a comparative study of them.*
Key words: *cornering, oversteering, understeering, passenger car, manoeuvrability, lateral acceleration.*

1. INTRODUCTION

From the existing bibliography in the field, from the specialty books as well as from the scientific papers results continue preoccupations of the researchers and opening up of innovative research directions and development. Also, in order to reduce the costs of the research, results the trend of development and use the physico-mathematical models and the computer simulation environments that capture the possible variables in exploiting of the vehicles, and to allow a pragmatic interpretation of the results. In the experimental research there is a tendency of using the advanced technologies of the data acquisition and processing.

In assessing of the vehicles performance are used terms for the assessment of the motor performance (maximum power, maximum torque, hourly consumption, specific consumption, etc.) or for assessing the entire vehicle (acceleration, maximum speed, time and space for the vehicle start-up, etc.) but are not mentioned the parameters that specify the stability limits for different travel regimes of the vehicles [2]. Such parameters are difficult to specified, especially due to the variety of the driving vehicle regimes that may be encountered during the exploitation period of the vehicle. In order to maintain permanently the vehicle stability for the safety of the vehicle occupants from inside but also those from outside of the vehicles, especially in the context of the high speeds travel, these parameters need to be known for certain regimes most commonly encountered, so the driver to adapt the exploitation of the vehicle, without losing its stability.

In order to obtain the desired movement of the vehicle, the driver takes action through the on-board controls, but the real movement of the vehicle may differ from the require due to the disturbing forces (as a result of interactions between the car and the environment or interactions between different ensembles of the vehicle and whose value that cannot be changed by the driver) which are variable in time and have a random character. Thus, for the vehicle movement to be in accordance with the wishes of the driver, it must accomplish some corrections [13] through additional movement control.

In [11] has been presented an investigation about influencing the driver's behaviour intuitively by means of modified steering feel. For a rollover indication through haptic feedback a model was developed and tested that returned awarning to the driver about too high vehicle speed.

For as the vehicles cornering to be considered properly, the steered wheels must run without lateral sliding which requires the description of concentric circles by all wheels of the vehicle around a single point called instant center of cornering [2, 4, 8, 13]. At the vehicles the steering system may be Ackermann type, parallel, or anti-Ackermann type. The cars have a steering geometry between Ackermann type and parallel [4, 14], the steering wheels following a common instantly cornering center [2, 4, 8, 14].

The action of a lateral force F_y, which may be due to the centrifugal force, the side wind or the transversal inclination of the the road, determines the deviation of the wheel (which occurs due to the lateral elasticity of the tire) from the direction of initial displacement through an angle δ, also called lateral deviation angle or drift angle [4, 13]. The lateral deformation of the tire due to the elasticity determines the appearance of a deviation from the initial displacement direction thereby influencing the real trajectory of the vehicle. The value of the drift angle δ can be calculated as the ratio between the lateral force F_y and the coefficient of resistance to the lateral deflection of the tire k. At values over 12**…**18º of the drift angle, the car skidding may occur [12, 13]. According to the values of the lateral deflection angles of the tire wheels to the front axle and rear axle can be determined [2, 4, 7, 8, 10, 13] the *cornering* behaviuor of the *vehicle* (understeering, oversteering or neutral steering).

In the paper [1] it has been proposing a new estimation process to estimate tire-road forces, sideslip angle and wheel cornering stiffness and the results show the accuracy and potential of the estimation process, and a limitation in the estimation of the cornering stiffness. The paper [3] mainly investigates steady-state nonlinear cornering behaviour of vehicles under lateral load transfer.

A study under the handling characteristics of the road vehicles have been studied in the paper [9] and the cornering behaviour of the vehicle is analysed and the constant radius test and the constant speed test are discussed.

The experimental determinations under consideration are designed to reflect the cornering behaviour of the car, the tests being performed according to the constant radius method [5, 7, 16, 17, 18], following the assessment of the parameters that influence the maneuvrability and stability in cornering and *cornering* behaviour of the studied car.

With the CarSim software package it has been simulated the behaviour of the considered vehicles in the process of cornering in order to confirm the experimental results using the same method of constant radius. The facilities provided by the computer simulation programs of the vehicles dynamics are detailed in [15].

2. EXPERIMENTAL DETERMINATION OF THE PARAMETERS THAT INFLUENCE THE BEHAVIOUR OF VEHICLE IN CORNERING

The methods for determination the understeering coefficient are standardized [16], being designed as to enable the yields similar results in the case of repeating a test on the same conditions. They are four in number, two of them based on maintaining constant the vehicle speed (in one case varying the cornering radius, and in the other the rotation angle of the steering wheel) and the other referring to maintain constant the cornering radius, respectively to maintaining constant the *steering wheel rotation angle* [5, 7, 16, 17,18].

Within each method there are constant parameters, variable parameters that are measured or calculated [16]. The methods will produce equivalent results provided that they fulfill the same combination of speed - steering wheel angle - curve radius [16]. The methods for determining the understeer coefficient differs by space needed for testing the vehicle, driver ability and tools required.

The experimental method used to determine the parameters that influence the behaviour of the passenger cars in cornering is the constant radius cornering. This test method consists in test displacement of the passenger car at different speeds in a circular path of constant radius and recording the compensation angle necessary to preserve the trajectory depending on the velocity value.

The passenger cars used in tests were Citroën C4 1.6 HDI, Smart Forfour 1.3i, Seat Ibiza 1.4 16V and BMW 320d E46. The passenger cars were in good condition at the time of testing without problems at the steering system, proper oparation of these being verified in the last 1000 km traveled by each.

The experimental tests were conducted in the parking area of the commercial center (Polus Center Cluj) in the period 05.05.2015-06.05.2015 with agreement of the center management. Ambient temperature on the experiments days was 18-19 degrees Celsius.

The purpose of the measurements was to determine certain cornering parameters of the passenger cars depending on tyre pressure, axle load, nature and state of the road and tire type (summer tyre or winter tyre). For their determination were used as follows: *graduated steering wheel cover; a mobile phone; photo camera MPMAN MPSC1 type; 10 m measuring tape; 15 m of twine; chalk for marking; measuring apparatus of passenger cars decks distributed masses; measuring apparatus of steering angle of the steered wheels depending on the angle of rotation of the steering wheel; bags filled with sand, having weight 50±1 kg for modifying the loading on the axles of the vehicle.*

In order to determining the nature of the understeer or the oversteer for the studied passenger cars, using the method of *constant radius cornering* it was marked a circle with a radius of *15 m*, measuring previously the distance with the *measuring* tape and subsequently it was traced the circle using chalk and a twine. The center of the circle became the instant center of cornering. The passenger cars were driven so as to follow the circle, moving outside the circle.

For determining the angles with which the steering wheel has rotated we used a graduated steering wheel cover, a mobile phone (*switch to front* facing *camera*) and a landmark located between the steering wheel and the phone (Figure 1a). Thus, for driving straight, was recorded zero-degree angle.

Each passenger car has moved on the traced circle with different speeds *(5…40 km/h)* their maximum value of the speed being determined by loss of the car control (when it can no longer be maintained on the established path). Initially, it was determined the *steering wheel rotation angle* required for moving the car with the speed of *5 km/h*, then was determined the compensation angle of the steering wheel (see Figure 1a) necessary to maintain the trajectory of the passenger car when increasing the speed. The tests were performed with different axle loads, with different tire pressures, summer or winter tires and driveway on a dry or wet concrete.

After the tests, were performed the determination of the distributed masses on the car axles and the steering angle of the steered wheels depending on the *steering wheel rotation angle*.

The loads on car axle, depending on the additional masses wherewith were loaded the tested passenger cars were determined using *suspension tester with weigh Space APF 110* type controlled by the control unit *Space PFC 750* type, at *Department of Automotive Engineering and Transports from the Technical University of Cluj-Napoca.*

In order to determine the steering angle of the wheels depending on the rotation angle of the steering wheel have been used two rotating plates (Figure 1b) mounted below the wheels. From the straight ahead position, the steering wheel has rotated anticlockwise to the maximum steering angle of the steered wheels and then to the right. The interval between two consecutive measurements was *30 degrees* in the steering wheel measured by the method shown in Figure 1a.

The correspondence between the values of the *steering wheel rotation angle* and the steering angle of the steered wheels is captured in Figures 2a, 2b, 2c and 2d.

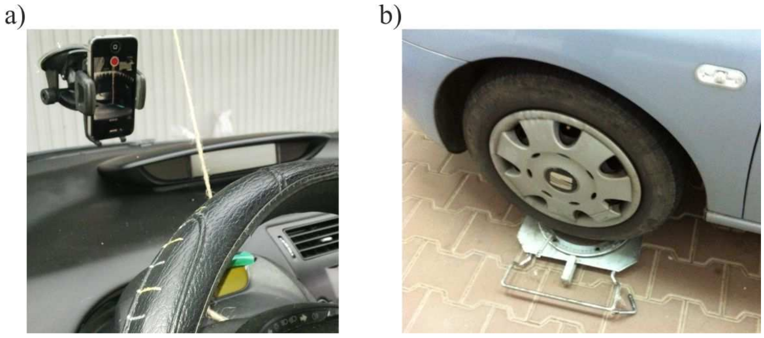

Fig. 1. Phases of the experimental measurements: Measuring mode of the *steering wheel rotation angle* (a) and determination of the steering angle of the steered wheels using rotating plate (b).

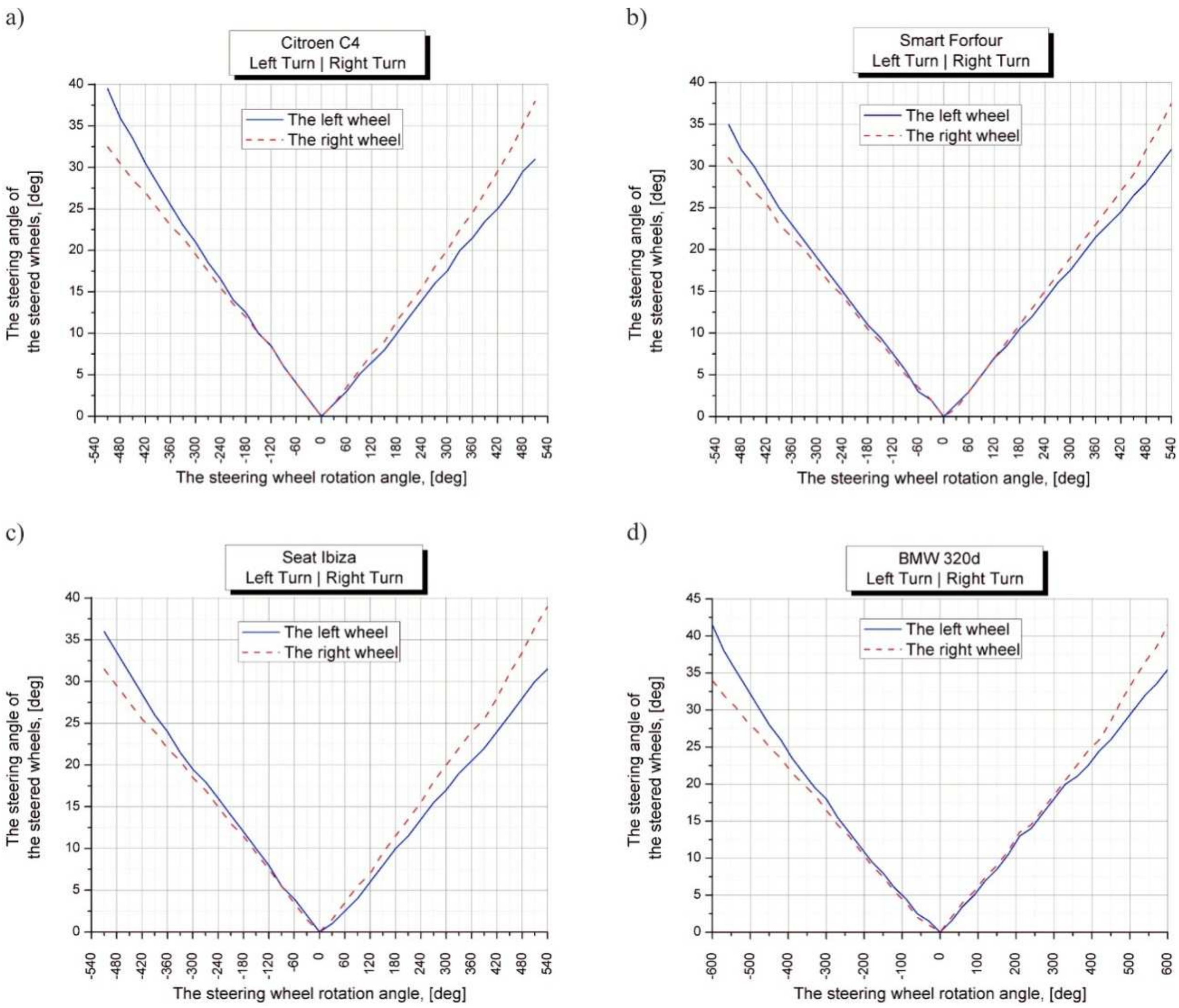

Fig. 2. The value of the steering angle of the steered wheels according to the steering wheel rotation angle to left and right: in the case of Citroën C4 car (a); in the case of Smart Forfour car (b); in the case of Seat Ibiza car (c) and in the case of BMW 320d car (d).

Among the factors that determine the car behaviour modification are: the mass of each axle, the condition of the rolling surface, tire pressure and the tire type. In the tests it has been changed the parameters above mentioned and it was followed the passenger cars cornering behaviour (Figure 3, Figure 4, Figure 5 and Figure 6).

The different loads of the axle were obtained by the use of sandbags weighing *50±1 kg*, and in some cases passengers. Table 1 captures the correlation between the indicated weight in Figures 5a, 5b, 5c and 5d, and the loading mode of the passenger cars.

Table 1

The correspondence between the loading mode and the mass distributed between the axles

Passager car	Charging mode	Mass-front axle, [kg]	Mass-rear axle, [kg]
Citroën C4	Unloaded	823	481
	Loaded (150 kg in the trunk)	808	641
	Loaded (passenger on the right front + passenger on the right rear + 50 kg in the trunk)	884	643
Smart Forfour	Unloaded	645	408
	Loaded (150 kg in the trunk)	637	554
	Loaded (passenger on the right front + passenger on the right rear + 50 kg in the trunk)	700	553
Seat Ibiza	Unloaded	691	449
	Loaded (150 kg in the trunk)	675	609
	Loaded (passenger on the right front + passenger on the right rear + 50 kg in the trunk)	685	555
	Loaded (passenger on the right front + 50 kg on the right front)	734	596
BMW 320d	Unloaded	745	700
	Loaded (100 kg in the trunk)	727	818
	Loaded (passenger on the right front + passenger on the right rear + 50 kg in the trunk)	795	867

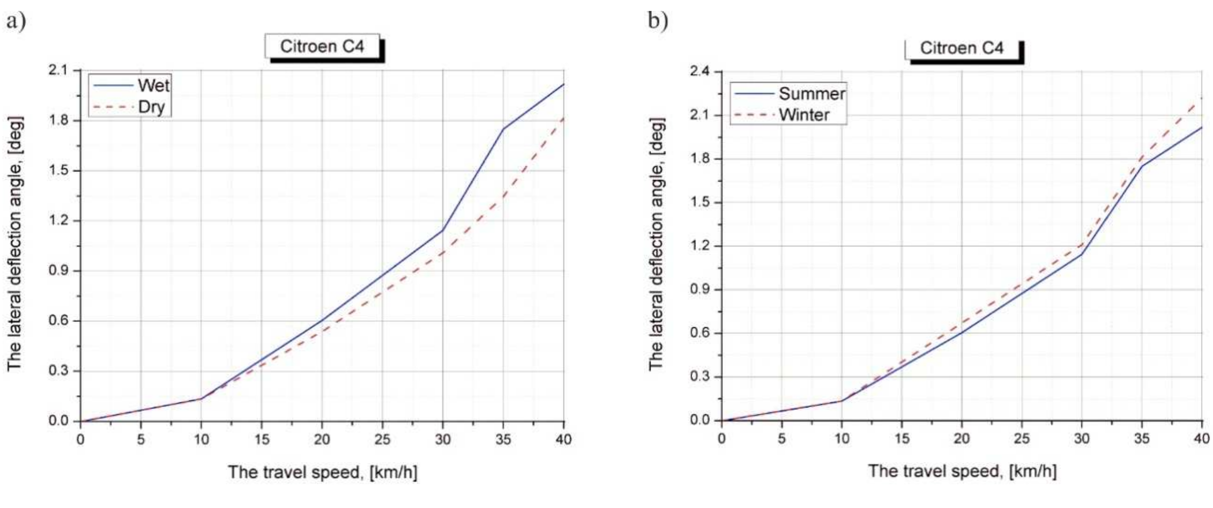

Fig. 3. The variation angle of lateral deflection of the tire according to the travel speed, for Citroën C4 car: for summer tires in the case of the rolling on the wet/dry surface (a) and for summer/winter tires in the case of the rolling on the wet surface (b).

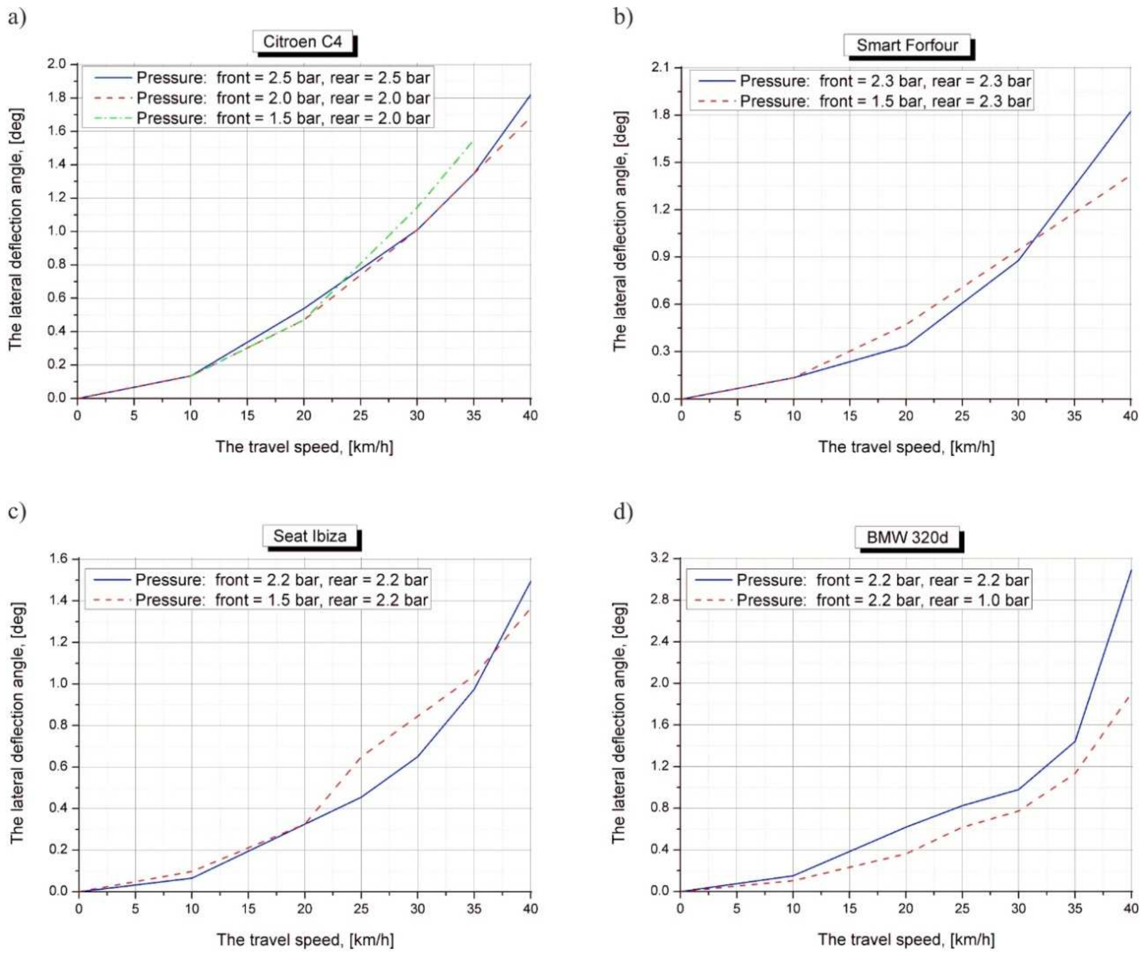

Fig. 4. The variation angle of lateral deflection of the tire according to the travel speed, for summer tires for different inflation tire pressures: for Citroën C4 car (a); for Smart Forfour car (b); for Seat Ibiza car (c) and for BMW 320d car (d).

The increasing degree of the giration angular speed (K_{vg}) for a motor vehicle which makes a cornering within which it rotates around the center of cornering with angular speed is defined by the relation [4]:

$$K_{vg} = \frac{\omega}{\theta} = \frac{v}{L + C_s \cdot \dfrac{v^2}{g}}, \tag{1}$$

where: θ is the average angle of the steered wheels; v - speed (denoted the speedometer fitted on the car), in m/s; L - wheelbase, in m; g - acceleration of gravity, in m/s^2; C_s - understeer coefficient given by the relation [5, 7, 16, 17, 18]:

$$C_s = \left(\theta - \frac{L}{R}\right) \cdot \frac{g \cdot R}{v^2}, \tag{2}$$

where: R is the radius of the circle on which the vehicle is moving, in m.

The understeer coefficient, in radians, and can be defined according to the relation [4, 14]:

$$C_s = \frac{G_1}{k_1} - \frac{G_2}{k_2}, \tag{3}$$

in wich: G_1 and G_2 represent the weights wherewith are loaded the front axle and the rear axle (it is considered equal with the static one for the situation when the car is moving uniform); k_1, k_2 - coefficients of resistance to lateral deviation of the front tires and the rear tires. In the particular case of neutral cornering, C_s is null, in the case of vehicle is understeering $C_s > 0$, and if vehicle is oversteering $C_s < 0$ [4, 7].

The increasing degree of the lateral acceleration (K_ℓ) is defined by the relation [7, 14]:

$$K_\ell = \frac{v^2}{g \cdot R \cdot \theta} = \frac{v^2}{g \cdot L + C_s \cdot v^2}. \tag{4}$$

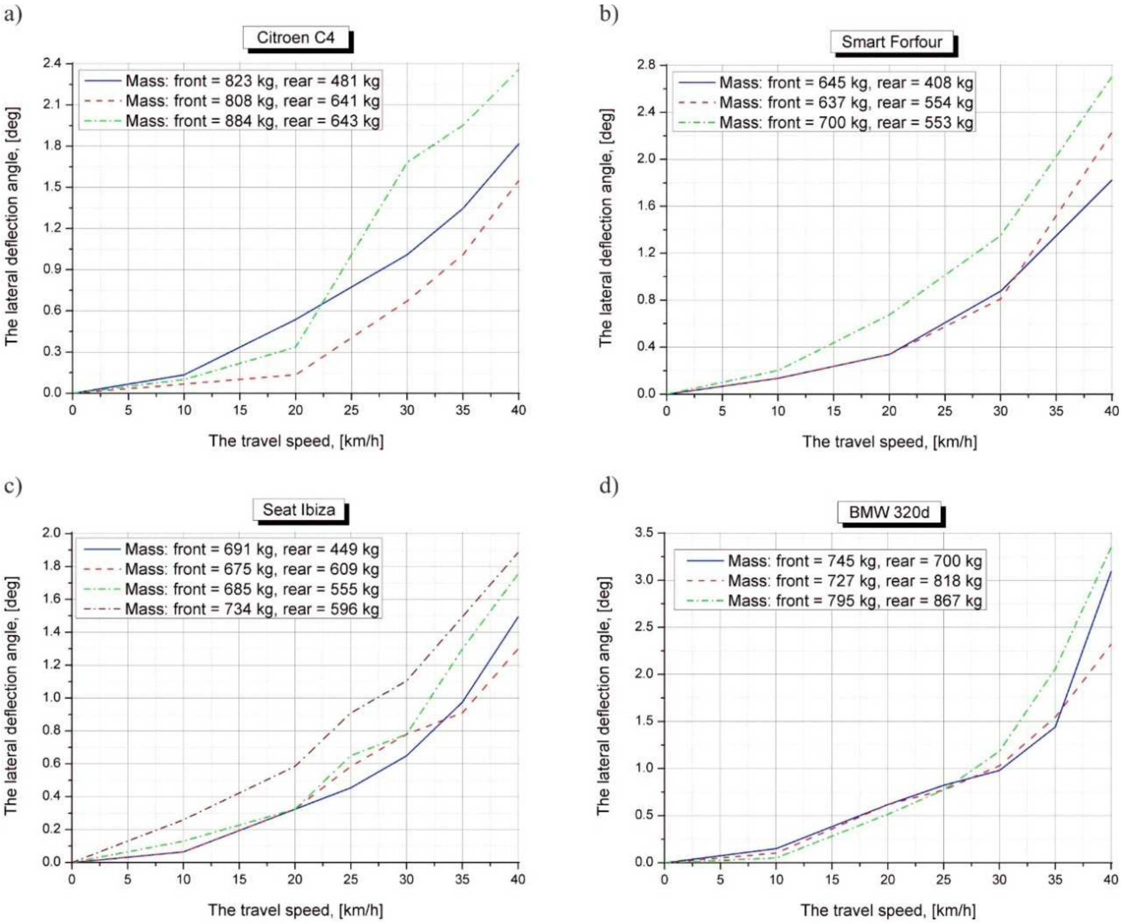

Fig. 5. The variation angle of lateral deflection of the tire according to the travel speed, for different mass distributions on the car axle: for Citroën C4 car (a); for Smart Forfour car (b); for Seat Ibiza car (c) and for BMW 320d car (d).

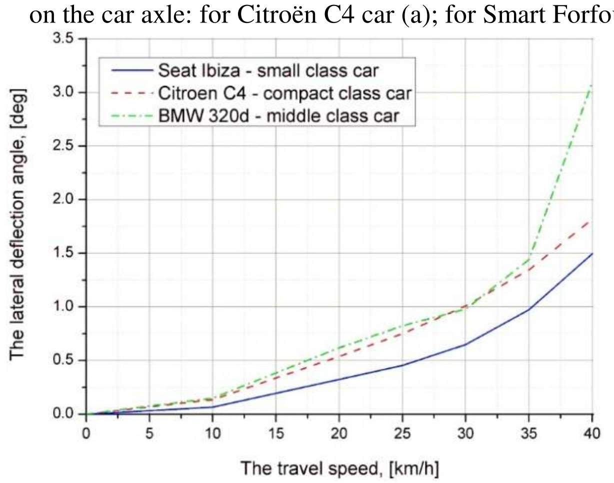

Fig. 6. The variation angle of lateral deflection of the tire according to the travel speed for different classes cars in unloaded state.

At the modification of the steering wheel position and by default the steering angle of the steered wheels, among the effects produced include the changing of the lateral acceleration and the gyration coefficient [7].

Referring to these parameters (K_{vg}, K_ℓ - depending on the speed) after carrying out the tests and processing have been achieved results with graphic interpretation and for example, in Figure 7a and 7b is surprised the Seat Ibiza vehicle case. The results confirm the understeer of the vehicle.

Lateral acceleration was considered according to the relation [5, 6, 7]:

$$a_y = \frac{v^2}{g \cdot R}\text{, in g,} \tag{5}$$

where g is in m/s^2.

Based on the experimental data it can be obtained results with a graphic interpretation to illustrate the variation of the *steering wheel rotation angle* and the angle of lateral deflection of the tire based on the lateral acceleration, according to the recommendations [16]. For example, in the Figure 7c and Figure 7d it can be observed the results for Seat Ibiza passager car and for the other cars the procedure is the same.

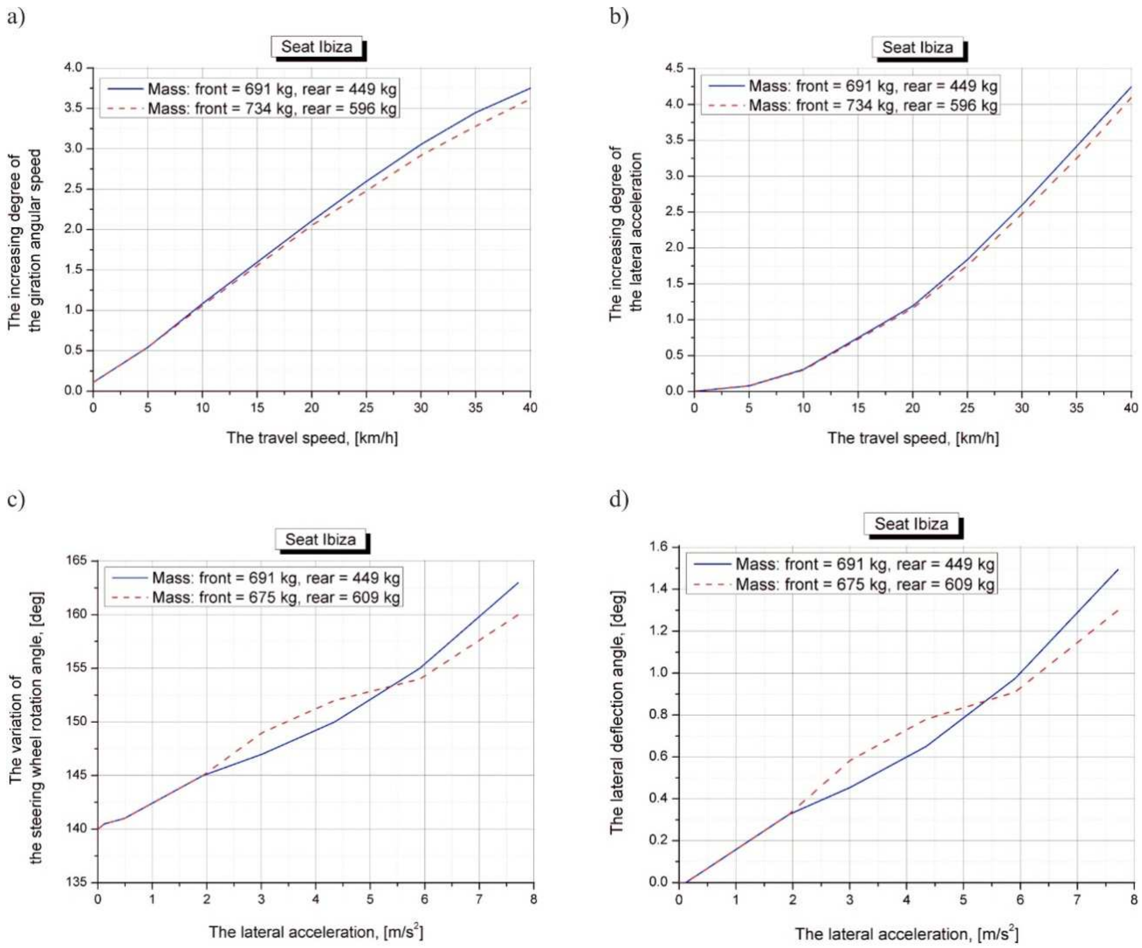

Fig. 7. The understeer characteristic of the Seat Ibiza car, for different mass distributions on the car axles: the increasing degree of the giration angular speed depending on speed (a); the increasing degree of the lateral acceleration depending on speed (b); the variation of the *steering wheel rotation angle depending* on the lateral acceleration (c) and the variation of the lateral deflection angle depending on the lateral acceleration (d).

3. COMPUTERIZED SIMULATION

The simulation was performed with simulation software CarSim for the passenger cars Seat Ibiza, Citroën C4 and BMW 320d, under the same conditions in which were performed also the experimental determinations, thus aiming to obtain comparative results.

For the assessment of the understeering or oversteering trend for the studied passenger cars is choosing the test type according to ISO 4138 [16], the method of constant radius cornering. This standard has predefined the radius value of the circle on wich are moving the cars as being *40 m*, which is a recommended value, it can be changed. In the experimental tests were considered the circle radius equal to *15 m*, but studied passenger cars have moved outside the traced circle, but the simulation program, considers that the introduced radius as being the minimum radius cornering, by choosing the radius equal to *16m.*

Among the specific parameters of the test there is also the grip coefficient that characterizes the nature and condition of the running surface. Thus, for a concrete/asphalt dry running surface is selected the value *0.85* and for the wet condition is selected the value *0.5*.

In the Figure 8a is represented the behaviour of the passenger car *Citroën C4* in case of its movement on a dry rolling track surface or wet one. It is observed that the loss of control in the case of wet condition occurs at a slower speed than for dry condition on the rolling track surface.

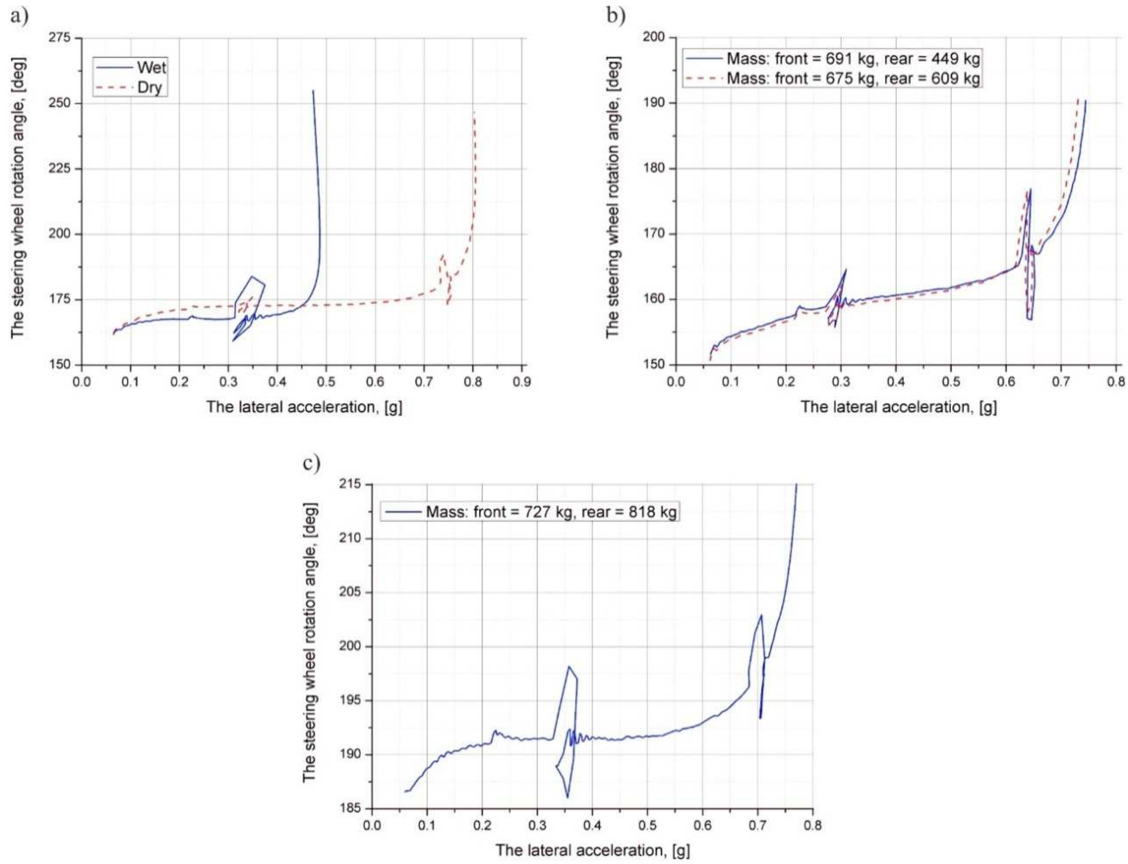

Fig. 8. The variation of the *steering wheel rotation angle depending on the* lateral acceleration (*g* - the gravitational acceleration): for different status of the rolling road surface for Citroën C4 car (a); for different mass distributions on the car axles, for Seat Ibiza car (b) and *for* BMW 320d car (c).

Taking into account the Table 1, Figure 9a illustrates a greater understeer tendency if the analysed passenger car is loaded with passenger (approx. *75 kg*) and a sandbag on the right-front, compared to the situation in which it is unloaded. Similar results were eperimentaly obtained (see Figure 5c).

In the computerized simulations, in addition to the variation of the understeering coefficient based on the lateral acceleration (Figure 9a) it has been follow also the variation of the *steering wheel rotation angle* according on the lateral acceleration (Figure 8a) and according to the angle of lateral deflection of the tire (Figure 9b), and to get an image of the wheels behaviour has been displayed too the angle variation of the lateral deviation of each tire depending on the time. The time variation actually involves the speed variation within the simulation, this increasing from 5 km/h up to the maximum value corresponding to loss of control for the passenger car.

The simulation results shown in Figure 8c corresponding to a load with two sandbags (having weight of *50 kg* each) in the trunk, so as to obtained a higher loading at the rear axle compared to the front axle, but the passenger car keeps their understeering tendency. This result was obtained experimentally too (see Figure 5d).

In the case in which is analysed the behaviour of the passenger car on its movement in a circular path by different radius (see Figure 9c) it’s observed that once with the increase value of the radius of the circle, the steering angle of the steered wheels is reduced, normal appearance and easy to guess, but it also reduces the drift angle of the directories axles of the wheels, whereas it reduces amount of inertia force. According to the Figure 9d, where driving the passenger car in a circular path, on left cornering, the angle of lateral deviation of the tire has the highest value at left front wheel, followed by the right-front, left-rear and right-rear wheel.

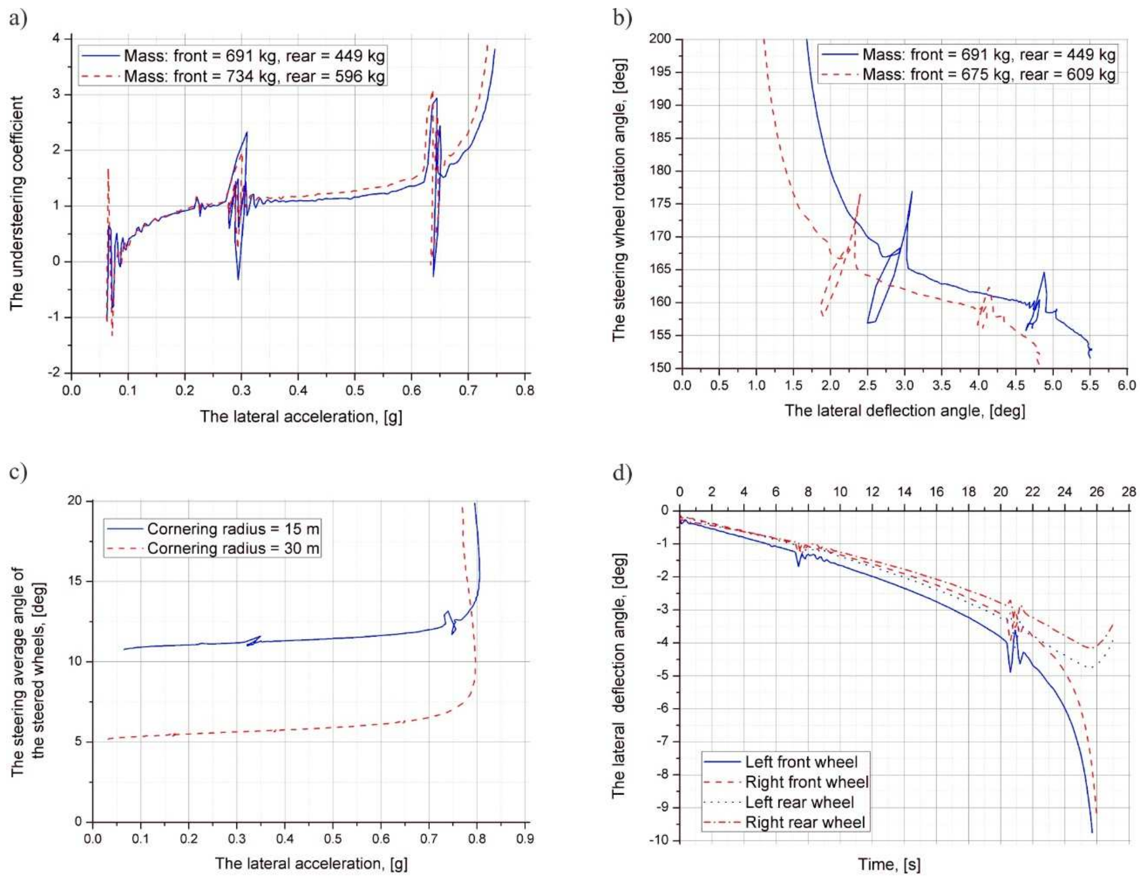

Fig. 9. Results of the computerized simulations for the studied vehicles: the variation of the understeering coefficient depending on *the* lateral acceleration, for different mass distributions on the car axles, for Seat Ibiza car (*g* - the gravitational acceleration) (a); the variation of the *steering wheel rotation angle depending on the* lateral deflection angle of the tire for different mass distributions on the car axles (Seat Ibiza) (b); the variation of the steering average angle of the steered wheels depending on *the lateral acceleration, for different cornering radius, for* Citroën C4 car (*g* - the gravitational acceleration) (c) and the variation of the lateral deflection angle of the each wheel tire depending on time (Seat Ibiza) (d).

4. CONCLUSIONS

Following the studies and the research undertaken in order to develop this paper were found the following:

- according to the obtained results we can say that the studied passenger cars steering systems are between Ackermann and parallel, the wheel inside of the cornering has a higher angle than outside it (see Figures 2a, 2b, 2c and 2d);
- the most unfavourable behaviour was obtained for loading the car with passenger in the front right of the car, passenger on the right rear and a sandbag weighing *50 kg* in the trunk; in the case of Seat Ibiza car the most unfavourable behaviour it was obtained for the loading with a passenger and a sandbag, both being positioned in front right of the car; first loading case is frequent encountered, the second case having the purpose to highlight the understeering trend of the passenger cars where increase the mass spread over the front axle (all unloaded passenger cars had the mass on the front axle greater than to the rear axle);
- the level of manoeuvrability of the cars is higher on a dry running surface *to the detriment* of the wet one (see Figure 3a) and with summer tires *to the detriment* of the winter tires (for presented testing conditions) (see Figure 3b);
- the decreasing tire pressure at the front axle wheels for passenger cars to which the engine and driving axle are placed in front, leads to reduce the drift angle (compared to the situation in which the pressures are approximately equal) with increasing the

speed travel (see Figures 4b and 4c); for passenger cars with front engine and rear driving axle, the phenomenon is reversed, thus the manoeuvrability is increasing at decreased pressure of the rear axle tires;

- reducing the rear axle wheels tire pressure in the case of BMW 320d passenger car improves its manoeuvrability (see Figure 4d);
- in the case of BMW 320d passenger car, although in two loading cases the distributed mass on the rear axle was greater than the one assigned to the front axle, it has kept the understeer characteristics (see Figure 5d);
- experimentally, for the unloaded state, the small-class car (Seat Ibiza) had the lowest drift angles (see Figure 6);
- the variation modes of the parameters that influence the manoeuvrability allow the determination of the understeering or the oversteering characteristics of the passenger cars (see Figures 7a and 7b);
- the simulation results confirm those experimentally obtained, so is justified the analysis of the dynamic behaviour of a vehicle found at the planning stage;
- the simulation software allows modifying a series of parameters as close as possible to the model used in the simulation by the real one;
- the obtained graphs have a high degree of confidence;
- the simulation allows the determination of certain parameters that would be difficult to determine experimentally or require a specialized equipment (eg: longitudinal forces, transversal and normal forces occurring between the tire and the rolling surface, the compression spring level of the suspension system, etc.).

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STUDIU COMPARATIV ASUPRA COMPORTAMENTULUI DINAMIC ÎN VIRAJ AL AUTOTURISMELOR DIN CLASE DIFERITE, PRIN METODE EXPERIMENTALE ŞI DE SIMULARE

Rezumat: Lucrarea prezintă un studiu - prin metode experimentale și de simulare **-** asupra comportării autoturismelor din clase diferite la deplasarea în viraj, aceasta fiind o situaţie frecventă de pierdere a controlului lor şi producere a accidentelor rutiere. De asemenea, studiul încearcă să ofere o imagine cât mai clară asupra modificării gradului de maniabilitate al autoturismelor în cazul diferitelor încărcări, astfel încât conducătorul auto să conştientizeze acest lucru, adaptându-şi stilul de conducere atât la condiţiile de drum cât şi la condiţiile de încărcare. Diferitele stări ale suprafeţei căii de rulare determină variaţia coeficientului de aderenţă, acesta nemodificând doar limita la care apare deraparea, ci şi comportamentul întregului autoturism până la atingerea acestei limite. În cadrul determinărilor experimentale, valorile parametrilor variaţi s-au ales astfel încât să caracterizeze cazuri reale, frecvent întâlnite, de exploatare a autoturismelor în procesul de virare, ținând seama de factorii care influențează deplasarea lor și tendința de rulare în curbe. Simulările computerizate au urmărit studierea comportamentului autoturismelor la deplasarea în viraje, pentru diferite condiţii de exploatare, evidenţiindu-se astfel parametrii a căror variaţie determină modificarea gradului de maniabilitate al acestora. Rezultatele obținute, atât prin metode experimentale, cât și de simulare computerizată, sunt cu interpretare grafică, oferind posibilitatea unui studiu comparativ al acestora.

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