NEW APPROACH TO MEASURE THE VEHICLE CENTRE OF GRAVITY HEIGHT

Petr Hejtmánek[1], Ondřej Blaťák[2], Jan Vančura[3]

Summary: The vertical position of the car's centre of gravity is one of the main parameters that influence vehicle handling and thus also the active traffic safety. The vehicle handling is nowadays frequently researched with the help of mathematical simulations, but for these it is necessary to provide correct values of the individual parameters of the vehicle. This study presents new approach to the measurement of the centre of gravity height with the help of a device which is primarily designated to measure the vehicle's moments of inertia. This method utilizes the influence of the centre of gravity height on the value of the measured oscillation period of the designed device. The method is verified, first on the known parameters and then on the two vehicles.

Key words: centre of gravity height, moment of inertia, test rig, experiment

INTRODUCTION

The vertical position of the centre of gravity is one of the fundamental parameters that influence vehicle handling a thus also the traffic safety. The higher the centre of gravity the greater the load transfer between the wheels during the driving manoeuvre, i.e. turning, breaking and acceleration. Usually, with the increase of the wheel load transfer the vehicle's driving limits decrease (usable tire forces), and it is so due to the decrease of the tire relative forces (longitudinal and lateral) with the increasing load. Except for the decrease of the vehicle's limits, also the increase of the centre of gravity height influences the vehicle handling and its rollover sensitivity. This factor is critical for the vehicles with great height of the centre of gravity (SUVs, vans, and pickups) which are more rollover sensitive then common passenger cars. Therefore, the effort of the designers should be to reach the lowest possible values of the centre of gravity height. However, this parameter may be in contrast to the other criteria of the vehicle, i.e. comfort of the passengers, view from the vehicle, etc.

Since the centre of gravity height belongs to the fundamental parameters of a vehicle, along the vehicle weight, it is necessary to focus on the influence of the centre of gravity height on the vehicle handling, for example, with the help of vehicle simulations. To obtain

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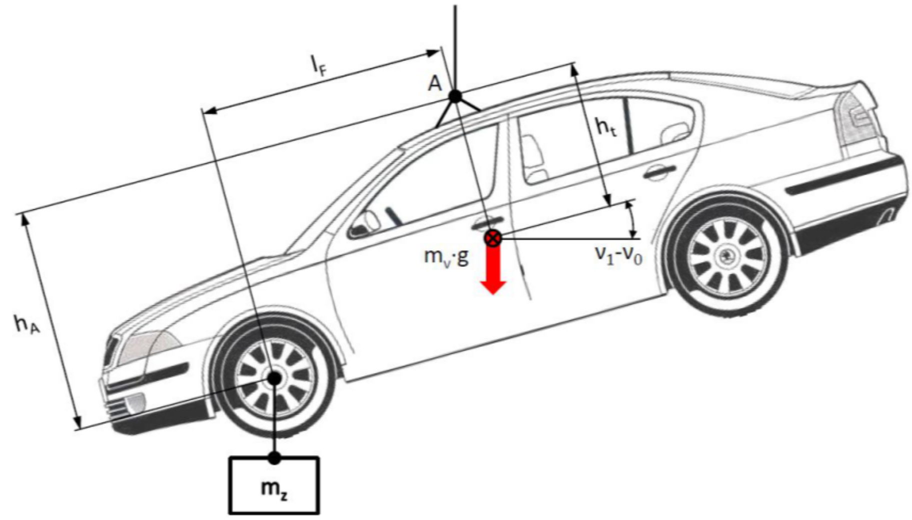
valid results of simulations, it is necessary to ensure correct values of the vertical position of the centre of gravity, however to measure the centre of gravity if far more difficult than to measure its weight. One of the basic methods to identify the vertical position of the vehicle's centre of gravity is the "tilting method" which require elevating the front end or the rear end of the vehicle. However, this approach has many inaccuracies caused by the tire and springs deformations, motion of fuel, coolants and lubricants, influence of the longitudinal forces in the tire contact patch, and others. On the other hand, a very precise is the "swinging method" which is based on the device which functions as a swing with lateral rotation axis, where the centre of gravity is levelled perpendicularly to the rig rotation axis. Subsequently, a specific weight is placed on the device in a specific position and the centre of gravity height is calculated from the tilt angle of the test rig, the principle of this method is introduced in the Fig.1.



Source: (1)

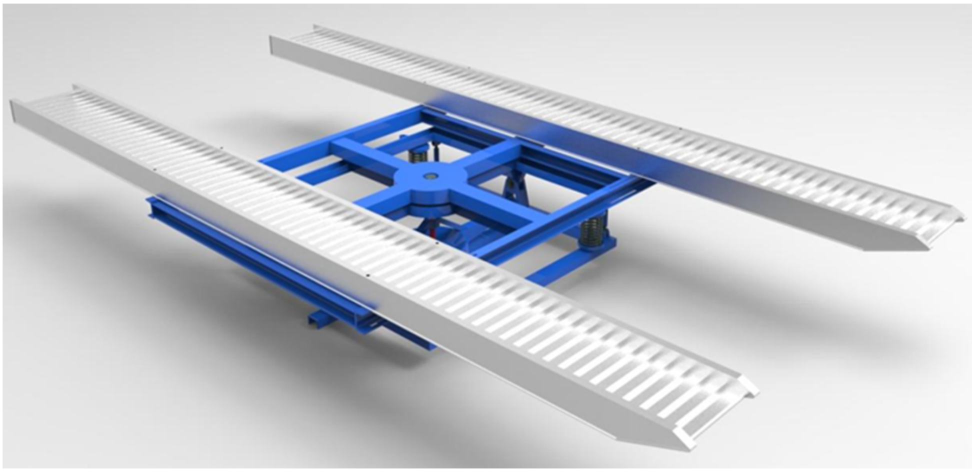
Fig. 1 – Principle of swinging method for measurement of the centre of gravity height

The study by The University of Michigan from 1991, states that this method reaches the accuracy up to 5% and repeatability up to 1% (2). Also the errors caused by the deformation of springs and the motion of fuel, coolants and lubricants is lower, since the desired tilt change of the vehicle is much lower than with the tilting method. Moreover, it is necessary to prevent any longitudinal motion of vehicle sprung mass, since the accuracy considerably depends on this motion. Although these laboratory methods bring satisfactory results, their main disadvantage is in the need to design a special device. Therefore, modern studies focus on the methods that identify the horizontal position of the centre of gravity during the driving manoeuvre. These methods utilize the dependency of the load transfer between the wheels during the vehicle's dynamic motion. Since the measurement of the wheel load during the driving is complicated, measurement of other vehicle parameters is utilized. For example, Barazaji (3) in his work set up a method of calculation of the centre of gravity height of a commercial vehicle with a semitrailer with the help of the measurement of the pressure change in air springs during a breaking manoeuvre. While the relative accuracy seems to be sufficient, the measurement repeatability is low, which could be caused by many neglected factors: e.g. tilt of sprung masses, load transfer through the suspension, tire deformation, etc. These factors may be included in the method of effective tire radius measurement (4). The effective tire radius is also dependent on normal load and from its change, during the dynamic manoeuvre, it is also possible to determine the centre of gravity height. The disadvantage of this approach is the need to consider the constant radial tire stiffness and the usability only for vehicles with the front-wheel drive. The accuracy of this method is approximately 10%.

Based on the above, each method has its disadvantages, and therefore, this study focuses on examination of the efficiency of a new method based on the determination of the vertical position of the centre of gravity with the help of the vehicle's moment of inertia.

1. METHOD'S PRINCIPLE

The new approach to the identification of the centre of gravity height makes use of the moment of inertia measurement principles with the help of the physical pendulum method. At the Institute of Automotive Engineering (IAE), Brno University of Technology (BUT) a test rig (Fig. 2) has been constructed for measurement of the vehicle's moments of inertia to three mutually perpendicular axes with the physical pendulum method.



Source: Author

Fig. 2 – Test rig for measurement of the vehicle's moments of inertia

The test rig consists of several levels which may be connected and set so the moments of inertia to all three axes could be measured. The main principle of this device is in the determination of the moment of inertia based on the relation between the value of the period of free rotary oscillation and the value of the moment of inertia. The opposed coil springs ensure the oscillating motion for the measurement of the roll and pitch moment of inertia. The torsional spring provide measurement of the yaw moment of inertia. Although, in reality, it is a damped oscillation (i.e. the damping influences the oscillation period), previous studies found out that the damping is insignificant (6). Fig. 3 demonstrates the derivation of the relation between the moment of inertia and the oscillation period, the detailed derivation can be found in (5).

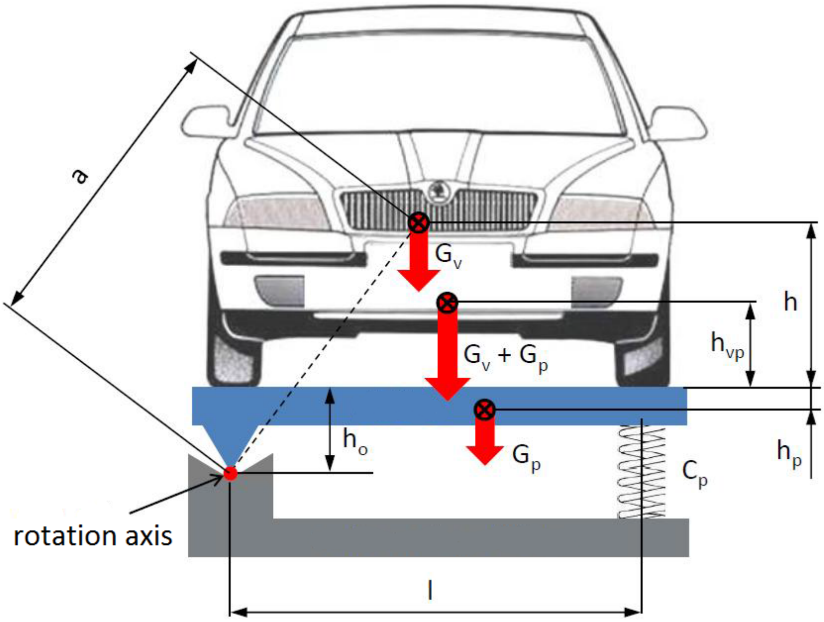


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Fig. 3 – Principle of the roll moment of inertia measurement

$$I = \frac{C_p \cdot l^2 - G_v \cdot (h_0 + h) - G_p \cdot (h_0 - h_p)}{4 \cdot \pi^2} \cdot T^2 \qquad (1)$$

Where:

C_p	coil spring stiffness
G_v	vehicle weight
G_p	pendulum weight
I	moment of inertia of vehicle and pendulum about an rotation axis
l	distance form spring to rotation axis
h	vehicle centre of gravity height
h_o	distance from rotation axis to pendulum floor
h_p	distance from pendulum centre of gravity to pendulum floor

This formula solves the moment of inertia for the whole system, i.e. the vehicle and the rotating parts of the test rig. To determine the moment of inertia of the vehicle itself it is necessary to subtract the moment of inertia of the rotating parts, and recalculate measured moment of inertia with respect to the test rig rotation axis to the vehicle centre of gravity with use of Steiner theorem. Nevertheless, to derive formula to calculate the vertical position of the centre of gravity, this basic form is sufficient. From the given formula it is evident that the measured moment of inertia to the rotation axis of the test rig depends, among others, on the centre of gravity height and spring stiffness. If the spring stiffness was changed (i – stiffness modification coefficient) then only the pendulum oscillation period would change, the vehicle centre of gravity height and the overall moment of inertia remain same (the influence of the change in the weight of the spring and its moment of inertia is small, so it may be neglected).

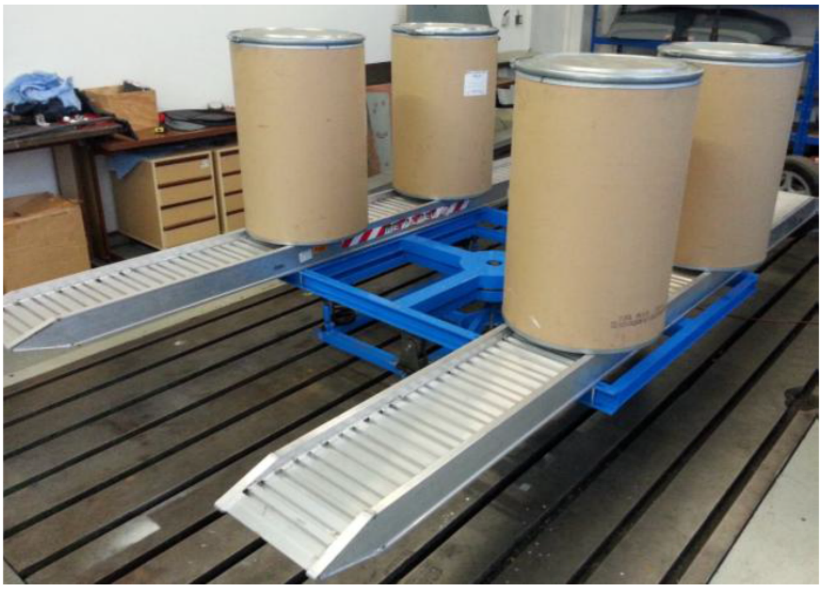
When using two sets of springs into the test rig then the following formula is used to determine the horizontal position of the centre of gravity:

$$h = \frac{C_p \cdot l^2 \cdot \left(i \cdot T_2^2 - T_1^2\right) - G_p \cdot \left(h_0 - h_p\right) \cdot \left(T_2^2 - T_1^2\right) - G_v \cdot h_0 \cdot \left(T_2^2 - T_1^2\right)}{G_v \cdot \left(T_2^2 - T_1^2\right)} \tag{2}$$

Even though a specialized device is needed to determine the horizontal position of the centre of gravity, its main advantage is its versatile application. The accuracy of the identification of the moment of inertia with the help of the physical pendulum method is very sensitive to the accuracy of determination of the angular oscillation period, accuracies and sensitivity of the measurement are analysed in (6). To determine the oscillation period the time history of the angular velocity is used, from which the oscillation period is calculated by the regressive analysis with 0.0001s accuracy.

2. MEASUREMENT

To evaluate the applicability of the methodology, first a measurement of the vertical position of the centre of gravity of an object with known geometrical and weight parameters was carried out. For this purpose a soft-grained filter sand was used. Sand was in four containers of a simple shape which were almost half full (Fig. 4). From their weight, volume, and precisely determined position of the barrels with respect to the device's rotation axis the moment of inertia of the sand in the containers was determined.



Source: (7)

Fig. 4 – Measurement of four containers with sand

The total weight of the sand was 600kg. To determine the horizontal position of the centre of gravity the moment of inertia to the device's longitudinal axis was measured. No transfer of the sand occurred (so the measurement accuracy was not affected) since the oscillation period was relatively high and the tilt angel very small. Measurement order was as follows: the barrels with sand were properly placed on the measuring device and the oscillation period for the basic spring's stiffness was measured. Subsequently, the springs enabling free oscillating motion were replaced by a spring with lower stiffness (50%), thus the oscillation period was prolonged (approx. 45%). The sand's horizontal position of the centre of gravity was calculated from the measured values of the period and other known parameters. Tab. 1 provides the comparison of the measured and derived values of the sand's vertical position of the centre of gravity, the resultant values given is the arithmetic mean of 10 repetitions. From the results, it may be concluded, that the accuracy of the measurement of the centre of gravity height is approximately 4.5% with the use of proposed method, which corresponds to the accuracy of the swinging method, and also provides a better results than on-line methods.

Tab. 1 – Sand centre of gravity height comparison

Estimated	Measured	Difference
[mm]	[mm]	[%]
193.7	202.5	+4.5

Source: Authors

3. METHODS COMPARISON

Next phase of this study is to compare the new approach to the tilting method. Therefore, an experimental vehicle from IEA was used: Formula Faster Ford 1600. The vehicle had its dampers replaced by stiff rods, and thus an alteration in position of sprung mass with respect to unsprung masses was prevented. Also no alteration in the formula's vertical position of the centre of gravity appeared. The weight of the vehicle was 400kg. As it may be seen in the Fig. 5, the load transfer during the elevation was not measured on the wheels but on the front part of the frame, therefore another negative influence was eliminated, i.e. tire deformation with the increased load. The vertical position of the centre of gravity was then calculated in respect to the road and the static position of the vehicle. Measurement of the load transfer was carried out in several positions while the rear part was elevated and also the measurement was repeated several times to determine the repeatability of measurement, which was satisfactory (3.4%). Afterwards, the formula's centre of gravity height was determined with the help of the moment of inertia measurement method (see Fig. 6). The principle and method of measurement were identical to the measurement of the sand's vertical position of the centre of gravity. The formula was tightly fixed to the platform. The fuel tank was empty because the fuel motion could negatively impact the accuracy of measurement. In Tab. 2, the results of both measurements of formula's centre of gravity height are given and compared:

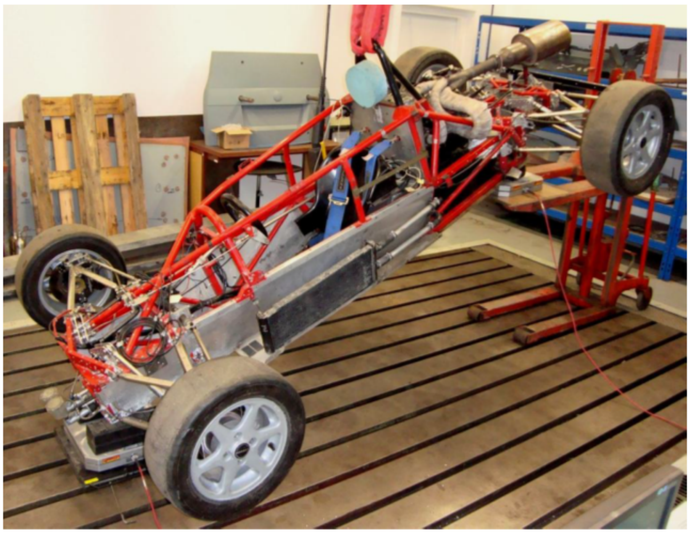


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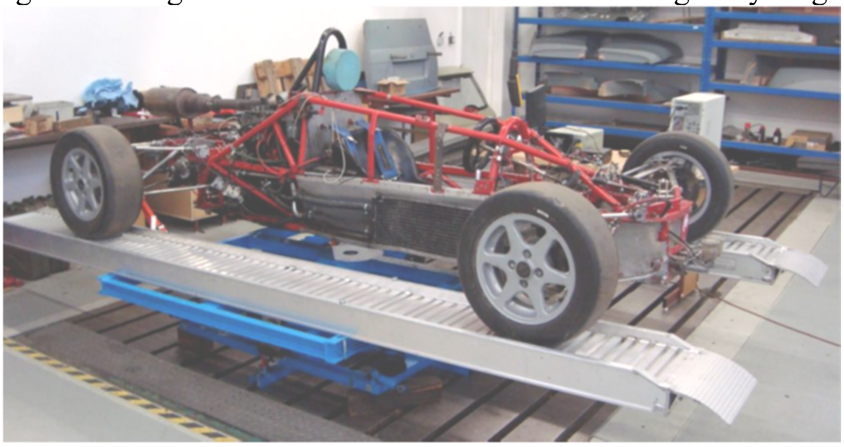
Fig. 5 – Tilting method for measurement of centre of gravity height



Source: (1)

Fig. 6 – Measurement on the new test rig

Tab. 2 Comparison of two methods for centre of gravity height measurement

Tilting method	Inertia method	Difference
[mm]	[mm]	[%]
237.2	231.7	-2.3

Source: Authors

The accuracy of these methods cannot be determined by the comparison of these results since the precise value of the formula's centre of gravity height is not given. Both approaches provide the measured value with certain inaccuracy. However, they may at least be compared. The results show that the differences in the determination of the centre of gravity height are relatively small (2.3%). Even though the tilting method is not very accurate (based on the previous research), when taking into consideration the number of negative factors being eliminated during the measurement, it may be concluded that the determination of the horizontal position of the centre of gravity with the help of moment of inertia measurement method is suitable for this type of vehicle.

4. THE CENTRE OF GRAVITY HEIGHT OF A PASSENGER CAR

The last experiment of this study is to measure the passenger car's centre of gravity height using the moment of inertia measurement method. As mentioned above, using the test rig the moment of inertia to three mutually perpendicular axes may be determined, while two of them are influenced by vertical position of the centre of gravity (roll, pitch). Measurement was so far used in respect to the longitudinal axis of the device, however, if employed the same principles with the respect to the lateral axis, we would get two resultant values of the vehicle's centre of gravity height which should be identical since the position of the vehicle on the platform does not change. Same as with the measurement of the Formula Faster Ford, the precise value of the height of the centre of gravity is not known, therefore the results serve only as means to carry out a comparison. For this measurement a vehicle with a higher centre of gravity was chosen on purpose, i.e. Škoda Yeti (see Fig. 7). Standardized measurement was carried out with two sets of springs, the vertical position of the centre of gravity was identified by oscillating about longitudinal and lateral axis. The fuel tank was full, the vehicle was fixed to the test rig with ratchet tie down straps, and the interior was empty with the overall weight of the vehicle being 1300 kg.

Source: (8)

Fig. 7 – Measurement of the centre of gravity height with new method

Tab. 3 – Results of centre of gravity height estimation for passenger car

Roll motion	Pitch motion	Difference
[mm]	[mm]	[%]
564.2	714.0	26.6

Source: Authors

The Tab. 3 shows the values of the horizontal position of the centre of gravity that are noticeably different, by 26.6%. On the basis of this negative result, sensitivity analyses of the individual parameters' effect on the accuracy of the measurement were performed. Among other, these analyses detected the need to measure the oscillation period more accurately as the height of the centre of gravity increases. However, this kind of precision markedly exceeds the repeatability rate of the oscillation period measurement and also the physical limits of the sensors used. This negative influence may be, to some extent, decreased by the use of two sets of springs with further difference in stiffness, at least by 800%. This kind of difference may be reached only by the employment of higher number of springs, which would lead to the rebuild of the test rig. From the sensitivity analysis, it is evident that the accuracy of the rig is very sensitive to precise measurement of spring stiffness and vehicle weight. However, the accuracy of the devices used to determine the values of these parameters is sufficient.

CONCLUSION

Based on the measurements and analyses carried out, it may be concluded that the current method to determine the centre of gravity height utilizing the moment of inertia is applicable to the vehicles with low position of the centre of gravity, i.e. formulas. Accuracy and repeatability of the measuring device is in this case sufficient and is comparable to the other methods. However, for common passenger cars, with their higher centre of gravity, there would be a need to design adjustment of the test rig so the overall spring stiffness could be markedly changed with the help of a higher number of coil springs. This alteration would make the measurement of the vertical position of the centre of gravity with the oscillation period less sensitive and thus the measurement of the vertical position of the centre of gravity would be more precise. However, these assumptions may be validated only by the above mention adjustment of the test rig and by carrying out more experiments.

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