

Experimental determination of the limit values of longitudinal accelerations of a motorcycle leading to loss of stability

Simona Hesapchieva^{1,*}, Ivan Chapkanov, Georgi Yanachkov²
 Burgas State University "Prof. DR. Asen Zlatarov, Prof. Yakim Yakimov Blvd. 1, Bulgaria¹
 Technical University Sofia, 8. Kliment Ochridski Blvd. Bulgaria²
 simona_hesapchieva@abv.bg

Abstract: Road experiments were conducted - when accelerating the motorcycle to the limit values of longitudinal geometric stability and the loss of contact of the front wheel with the road or reaching the "wheelie" phenomenon. From the theory of the motorcycle it follows that the critical accelerations depends on the height of the center of mass and its horizontal coordinate. In the presence of a passenger, the center of gravity is moved back and up, which leads to a decrease in the theoretical value of these accelerations. Therefore, the experiments were conducted on a motorcycle equipped with a suitcase and a passenger located on the back seat. The received information is recorded and visualized on a portable computer, and then processed in the Matlab and Excel environment. The results obtained from the experiments and the accumulation of databases can be used to create models for determining the influence of the driver's behavior, the passenger's influence, models for determining the behavior of the motorcycle and the comfort of the trip. During the measurements, the change in position of the driver and passenger is not taken into account.

Keywords: Motorcycle acceleration, wheelie, traffic safety, pitch angle, longitudinal accelerations

1. Introduction

The stability of two-wheeled vehicles during acceleration and braking is of critical importance for traffic safety. Transitions between these modes are particularly critical, as they lead to a great redistribution of weight between the front and rear wheels, changing the traction and dynamic characteristics of the system, leading to rear wheel slippage (during acceleration), locking or lifting of the rear wheel (during braking), or even complete loss of control. When a two-wheeled vehicle accelerates, the additional load on the rear wheel, which occurs due to the redistribution of the load, increases its traction, but at the same time the load on the front wheel decreases, which leads to instability in steering and limited ability to turn [1, 2]. When reaching the limit values of longitudinal acceleration, unstable conditions occur such as lifting the front wheel (wheelie), lifting the rear wheel (stoppie), slipping or complete loss of traction and reduced rolling resistance. In the scientific literature, theoretical and numerical models for the analysis of motorcycle instabilities are based on nonlinear tires (e.g. Pacejka model), multi-body simulations, and modal decomposition [3,4 and many others]. However, many of these approaches rely on simplifications that do not always reflect the real behavior of motorcycles under limit loads. Experimental determination of the critical accelerations is an important step towards validating these models and gaining a deeper understanding of the instability dynamics of two-wheeled vehicles. The use of inertial measurement units (IMU), sensors and GPS systems allows for highly accurate registration of motion parameters, including wheel slip, slip and change in the center of load [5,6,7 and other].

2. Importance of the mass center and theoretical limit values

The coordinates of the motorcycle's center of mass have a significant impact on its dynamic behavior, especially in acceleration and braking modes. In modern motorcycles, the tendency is for the load to be evenly distributed on both axles. This results in good motorcycle handling both during acceleration and braking. If the center of mass is positioned forward (the load on the front wheel is greater than on the rear wheel), better resistance to loss of contact between the front wheel and the road is achieved. Another advantage is the partial compensation of aerodynamic forces, which relieves the front wheel, which is particularly important for driving safety, especially at high speeds. If the center of mass is positioned rearward (the load on the rear wheel is greater than 50%), better braking properties of the motorcycle are achieved, and the risk of loss of contact between the rear wheel and the road and the occurrence of a longitudinal rollover is reduced.

The position of the total center of mass of the motorcycle, together with the rider, is shifted rearward and the rear wheel is loaded further.

The vertical coordinate of the center of mass h has a significant impact on the stable behavior of the motorcycle, especially in acceleration and braking mode. The high position of the center of mass during acceleration leads to a greater redistribution of load from the front to the rear wheel. With a higher load on the rear axle, more driving force can be applied, but stability during acceleration deteriorates and loss of contact between the front wheel and the road can occur if the vertical reaction in it becomes equal to zero.

In case of sudden acceleration in low gear, the amount of acceleration can be limited by the traction between the tire of the driving wheel and the road. Since the air resistance force is a function of the speed squared, maximum acceleration can be achieved at very low speeds in first gear on a smooth, improved road surface. In this case, it can be assumed that drag force $F_D=0$. The maximum acceleration is limited by traction, since the tangential reaction at the driving wheel cannot exceed the corresponding traction force, or the maximum driving force must be less than or equal to the maximum force obtained by the product of the adhesion coefficient μ and the vertical load [1]:

$$S \leq \mu N_r \quad (1)$$

where S indicates the driving force during acceleration, N_r normal reaction in the rear wheel.

Expressing the normal load, for the maximum acceleration in traction we get:

$$\ddot{x} \leq \frac{\mu g \frac{p-b}{p}}{\left(1 - \frac{h}{p}\right)} - \frac{F_D}{m} \quad (2)$$

The condition under which the loss of contact between the front wheel and the road will occur is met when the normal reaction in it becomes equal to zero ($N_f = 0$). In order to ensure stable movement of the motorcycle during acceleration without allowing loss of contact between the wheel and the road, it is necessary to fulfill the condition::

$$\ddot{x} \leq g \frac{b}{h} - \frac{F_D}{m}, \quad (3)$$

The present study aims to determine the limit values of longitudinal acceleration that lead to loss of stability of a motorcycle during acceleration. To achieve this goal, an experimental methodology has been developed, based on tests in a controlled environment (test track) with equipment for recording motion parameters, including linear and angular accelerations.

3. Selection and location of measuring equipment

In this study, a microelectromechanical system MEMS WT901 AHRS IMU sensor was used to measure horizontal and vertical acceleration in combination with a portable laptop on which the measurement data was recorded. It consists of a high-precision gyroscope, an accelerometer and a geomagnetic field sensor. The device can quickly determine the current real-time movement position of the module using a high-performance microprocessor, advanced dynamic solutions and the Kalman filter algorithm. The advanced digital filtering technology of this product can effectively reduce measurement noise and improve measurement accuracy. Maximum output data rate 200Hz. The output content can be arbitrarily selected, the output rate is adjustable from 0.2Hz to 200Hz. The parameters of the measuring device are presented in Table 1, and the measurement range and accuracy are in Table 2 [9].

Table 1: Equipment parameters.

Parameter	Specification
Working voltage	3,3V-5V
Current	< 25 mA
Dimensions	15.24mm x 15.24mm X 2.54mm
Data	Angles: X Y Z, 3-axis acceleration: X Y Z, 3-axis angular velocity: X Y Z, 3-axis magnetic field: X Y Z, 3-axis time, Quaternion
Output frequency	0,2Hz-200Hz
Baud rate	4800,9600(default),19200, 38400, 57600, 115200, 230400

Table 2: Measurement range and accuracy.

Measurement range and accuracy		
Sensor	Measurement range	Accuracy
Accelerometer	X, Y, Z, 3-axis ± 16g	Accuracy: 0.01g, Resolution: 16bit
Gyroscope	X, Y, Z, 3- axis ±2000°/s	Stability: 0.005g
Magnetometer	X, Y, Z, 3-axis ± 2 Gauss	Resolution: 16bit
Inclinometer	X, Y, Z, 3- axis X, Z-axis: ±180°, Y ± 90°	Stability: 0.05°/s

Conducting road tests on a motorcycle is always a challenge and carries risks for both the rider and the measuring equipment. The placement of the measuring equipment is often a problem due to the limited space and mounting options. The accuracy and reliability of the measurement is largely influenced by the correct placement of the sensor. In the present study, the MEMS device used to measure accelerations and rotations is mounted on the motorcycle tank in a horizontal position, as close as possible to the motorcycle's center of mass (Fig. 1).



Fig. 1 Installation of the measuring equipment

4. Organization of the experiment

To determine the limit values of the motorcycle acceleration in acceleration mode, a series of experiments were conducted on a smooth horizontal section of the road surface in both directions. The test is carried out on a motorcycle with the participation of a driver and a passenger. It begins when the motorcycle is at rest. The recording is started by the passenger, and the driver engages first gear and accelerates the motorcycle along a straight trajectory by abruptly releasing the clutch until the front wheel loses contact with the road. Then the motorcycle stops accelerating and begins a smooth and safe braking to complete rest. A few seconds later, the recording equipment is stopped and the experiment is repeated. The average duration of the experiments is about 15 - 20 seconds. Before the experiment, the motorcycle tires were heated. The results obtained are compared with the minimum theoretical accelerations.

For the test motorcycle, through which the limit accelerations were experimentally determined, a BMW R1200 GS 2014 motorcycle was used. The motorcycle is factory-equipped with active safety systems ABS, TC and ESP, which can be switched off at the driver's request. The motorcycle parameters are listed in Table 3. Before the start of the experiments, the motorcycle was filled with fuel until the tank was full. The tire pressure was according to the manufacturer's instructions - 2.5 bar in the front and 2.9 bar in the rear.

Table 2: Measurement range and accuracy.

Parameter	Dimension	Value
Engine		
Volume, V_h	m^3	1170
Diameter/ Stroke, D/S	mm	101/73
Power, N_e	kW	92
By rpm n_N	min^{-1}	7700
Torque, M_e	Nm	125
By rpm n_M	min^{-1}	6500
Number of cylinders	i	2
Type		Air/water cooled, spark-ignition horizontal boxer engine
Number of valves per cylinder		4, Intake d=40 mm, Exhaust d=34 mm,
Exhaust system		3-component catalytic converter
Transmission		
Clutch		anti-hopping wet
Gearbox		Constant mesh 6-speed gearbox
Primary transmission ratio		1
Transmission input ratio		1,650
First gear i_1		2,438
Second gear i_2		1,714
Third gear i_3		1,296
Fourth gear i_4		1,059
Fifth gear i_5		0,943
Sixth gear i_6		0,848
Gear ratio of final drive i_f		2,91
Final drive		Cardan shaft
Frame		
Type		Tubular steel frame with supporting drive unit, steel pipe rear frames

Suspension		
Front suspension		Telelever
Suspension travel	mm	190
Rear Suspension		Cast-aluminium single swingingarm with BMW MotorradParalever
Suspension travel	mm	220
Trail, a	mm	100
Geometrical parameters		
Wheelbase	p	1507 mm
Castor angle ϵ	o	25,5
Distance from front axle to center of mass*	a	739 mm
Distance from rear axle to center of mass*	b	768 mm
Brake system		
Front	mm	Hydraulically actuated twin-discbrake with 4-piston radial monobloc calipers and floating brake discs, 305 mm
Rear		Hydraulically operateddiscbrake with 2-piston floating caliper and fixed disc, 276 mm
ABS		Integral, partially integral, switchable
Wheels and tyres		
Front tyre, r_f		120/70R19
Rear tyre r_r		170/60R17
Overall dimensions and weight		
Length, L	mm	2207
Width with mirrors, B	mm	953mm
Seat height, H_s	mm	850/870
Mass, m	kg	238
Weight distribution	%	51/49
Permissible total weight, m_t	kg	450
Tank capacity	L	20
Driver		
Own mass	kg	103
Passenger		
Own mass	kg	45

Due to the presence of vibrations from the engine and others, some error is inevitably introduced into the measurements .

5. Experimental results

According to equation 1, the condition at which the loss of contact between the front wheel and the road will occur is when:

$$\dot{x} = g \frac{b}{h} - \frac{F_D}{m}$$

The calculation assumes that the entire mass of the passenger is assigned to the rear axle, and that of the driver is distributed in half between the front and rear axles.

Unlike automobile, the frontal area of a motorcycle is not constant. It is strongly influenced by the position and body of the rider and the presence of additional equipment. On some motorcycles, the fairings and windshield are available with different height and width settings. Therefore, it is difficult to determine the force from aerodynamic resistance theoretically with accuracy. In all cases, the speed of the motorcycle does not exceed more than 8,5m/s. The aerodynamic coefficient of the motorcycle is about $c_x=0.7$. The frontal area of the motorcycle without taking into

account the rider's participation is approximately $S=0,8$. Since the speed at which the front wheel loses contact with the road surface is relatively small in contrast to the acceleration achieved, in order to simplify the inequality, the assumption will be made that the aerodynamic force is approximately equal to zero. This assumption does not introduce an error of more than 0.05 g. According to table1. and the known methods from the literature for calculating the vertical coordinate of the center of mass, for the limiting acceleration is obtain:

$$\ddot{x} \approx 1 \text{ g}$$

The initial phase is characterized by an intense increase in the longitudinal acceleration of the motorcycle which also leads to a significant increase in vertical acceleration. As a result, a significant pitch angle is achieved.

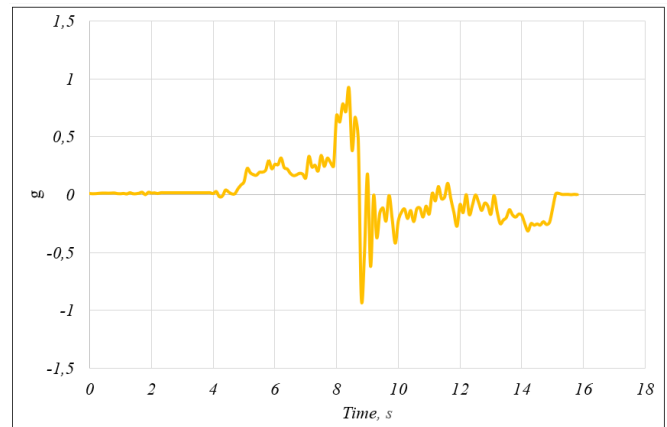


Fig.2 Longitudinal acceleration of the motorcycle

Fig. 2 presents the results of the longitudinal acceleration of the motorcycle. The acceleration begins shortly after the fourth second when the throttle is opened slightly above 50%. The motorcycle is accelerated with first gear engaged until the front wheel lifts off the road surface. The maximum value reached by the acceleration is 0.7 g, which is less than the theoretical value. This is due to the assumptions made in the theoretical calculation. The coefficient of traction is above the ratio b/h , the motorcycle cannot reach maximum acceleration, since the front wheel lifts off. With a smoother increase in speed (smoother opening of the throttle) and a smoother increase in longitudinal acceleration, the loss of contact between the front wheel and the road due to the increase in air resistance will not occur.

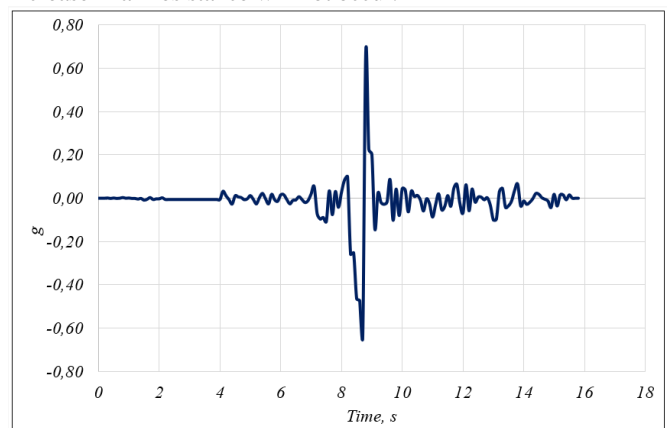


Fig.3 Vertical acceleration

As a result of the load transfer and the significant shift of the coordinate of the center of mass back and up, the normal reaction in the front wheel is exhausted and it loses contact with the road. Fig.3. shows the change in vertical acceleration. The maximum value of the vertical acceleration is 0.7g, which is reached with a delay of about 0.2 s compared to the maximum longitudinal acceleration. After landing of the

front wheel, as a result of the disturbances in the suspension, a slight fluctuation in the acceleration is observed until complete damping.

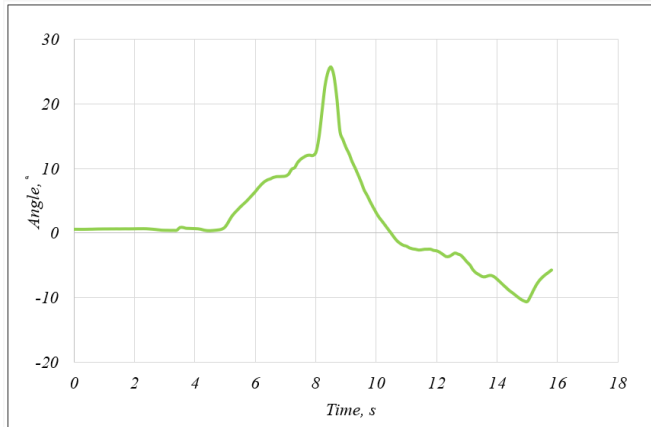


Fig.3 Variation in pitch angle

Fig.4. shows the measured pitch angle of the motorcycle. As a result of the load transfer and the compression in the rear suspension, a smooth rotation of the center of mass occurs. When reaching critical acceleration and lifting the front wheel (wheelie achieved), a jump in the pitch occurs. As a result of the reduction of the acceleration and the reduction of the load on the rear axle, the front wheel is again in contact with the road surface and the roll smoothly decreases. After the wheel lands, a roll in the opposite direction is recorded as a result of the deformation in the front suspension.

Conclusions

In this paper, the limit accelerations calculated theoretically and measured by a field experiment are presented. At the beginning, the influence of the center of mass and the redistribution of the load on the front and rear axles are clarified.

In an attempt to limit road accidents, the requirements for the active and passive systems of vehicles are increasing, which necessitates their constant improvement. This pressing topic is especially true for two-wheeled vehicles. The stability of the motorcycle's movement during acceleration and braking is of great importance for the safety of the driver and passenger. The transitions between these modes are particularly critical, as they lead to a sharp redistribution of weight between the front and rear wheels, changing the traction and dynamic characteristics of the system.

This emphasizes the need to accumulate knowledge and experience about the dynamic behavior of the motorcycle through road experiments in different modes. The focus of the study is on detecting the tendency for the front wheel to lift during acceleration and the rear wheel to lock up during braking, which leads to a significant decrease in stability and stability of movement, and in a more extreme case - to rollover and accidents. A methodology for measuring accelerations is presented. The analysis of the results shows that in modern motorcycles the grip boundary conditions are reached and exhausted very quickly, and active safety systems are not able to solve the problem of wheel lift fundamentally. The results obtained can be used in dynamic models studying motorcycle dynamics. Based on the results, optimizations can be made to the existing algorithms used in anti-lift and anti-lock systems.

Future research will be aimed at a thorough study of the influence of the passenger and the body position towards the driver on the stability and dynamics of the motorcycle and the capabilities of active safety systems to correct errors, especially from less experienced drivers. This is an insufficiently researched factor that has a significant impact on traffic safety.

Acknowledgements

The authors would like to thank t for the financial support to NPPO-06.

3. References

1. Cossalter V. Motorcycle Dynamics, Second English Edition, 2006
2. Sharp, R.S., & Limebeer, D.J.N. (2001). "A motorcycle model for stability and control analysis." *Multibody System Dynamics*, 6(2), 123–142.
3. Pacejka, H.B. (2012). *Tire and Vehicle Dynamics*. Elsevier.
4. Limebeer, D.J.N., & Sharp, R.S. (2006). *Journal of Sound and Vibration*, 288(4), 961–992..
5. Panzani G., Corno M. and Savaresi S. M., "Wheelie detection for single-track vehicles," 2013 European Control Conference (ECC), Zurich, Switzerland, 2013, pp. 956-961, doi: 10.23919/ECC.2013.6669206.
6. Nguyen Q. H., Nguyen C. Hoang H., T., Nguyen P. D. and Ngoc D. L. (2024) "Using IMU Inertial Sensor For Motorcycle Kinematics Analysis," 9th International Conference on Applying New Technology in Green Buildings (ATiGB), Danang, Vietnam, 2024, pp. 104-107, doi: 10.1109/ATiGB63471.2024.10717837.
7. Saipul Bahri, M. A. (2022). Validation of Cost-Effective Data Acquisition System on Motorcycle. *Progress in Engineering Application and Technology*, 3(2), 573-582.
8. BMW-Motorrad. (2004). BMW-Motorrad, Technology in detail, from <http://www.bmw-motorrad.com/com/en/index.html> Retrieved October 11, 2014
9. <https://www.wit-motion.com/>, online 15.09.2025