01A1025

MOTORCYCLE STEADY TURNING:
THE SIGNIFICANCE OF GEOMETRY AND INERTIA

D. Bortoluzzi, R. Lot, N. Ruffo

Motorcycle Dynamics Research Group
Dept. of Mechanical Engineering, University of Padova
Via Venezia 1, 35131 Padova, Italy
e-mail LOT@DIM.UNIPD.IT

Abstract

The primary way to control a motorcycle is the steering torque exerted by the rider on the handlebars. Basic steering properties of motorcycle can be evaluated in steady turning conditions. These properties can be also related to handling and stability of vehicle: if low steering torque is required on steady state cornering, the driver feels that the vehicle is maneuverable. Furthermore, if the steering torque has opposite sign with respect to the steering angle, the capsize mode is rather stable.

This paper deals with the effect of motorcycle geometric and inertial properties on steering torque in steady turning. The analysis is carried out by means of numerical simulations and experimental tests. Numerical simulations are carried out by means of a 11 d.o.f. multi-body model. Experimental tests are performed on a sport motorcycle equipped with instrumented handlebars and gyroscope transducers. The numerical results are compared to experimental data, obtaining good agreement. After this validation of the multi-body model, several numerical simulations are carried out in order to understand the influence of some geometric (like trail, castor angle) and inertial (like mass gravity center position, inertia moment) properties of the motorcycle on the steering torque. Steering torque is represented by contour plots, as a function of path curvature and forward speed. Finally, some dynamic simulations are carried out in order to examine the effect of the same parameters on the transient from straight running to steady turning.

Introduction

The study of motorcycle handling can be performed by analyzing its dynamic behavior during particular manoeuvres, in which the vehicle evidences its fundamental characteristics. Among the possible manoeuvres, the analysis of turning manoeuvre in steady-turning condition[1,2,3,4,5] and during transient from the straight-running to the steady-turning conditions[6,7] can give useful information about motorcycle behavior.

Motorcycle handling deals with a system composed of a rider and a vehicle, and the most important rider-vehicle interface is the steering system. The rider controls the motorcycle mainly through the torque he applies to the handlebars, and through the handlebars he receives a feedback from the motorcycle. Thus, the steering system transforms the steering action of the driver in an effective path followed by the motorcycle, and also allows the rider to evaluate the motorcycle's handling by means of the required steering effort.

The steering system is involved with two fundamental characteristics of the motorcycle. The first is called *manoeuvrability* and is the capability of the vehicle to perform quick manoeuvres according to the physical limits of the system (i.e. tire adherence). The second is called *handling* and is the capability of the motorcycle to perform fast manoeuvres requiring a small psychological-physic effort on the part of the rider[8,9]. This second characteristic is strongly related to what is required to rider's driving sensation.

Considering the steady-turning conditions, if a low steering torque is required, the driver feels that the manoeuvre is easily performed. Furthermore, if the steering torque required is zero, in absence of control the trajectory is kept constant and the amount of applied torque is proportional to the desired change of path.

The inward or outward curve direction of the steering torque required by a motorcycle to perform a steady-turn gives an insight into stability. When the applied torque is inward the curve (positive torque) the capsize mode of the vehicle is rather unstable. This is because in the absence of control the steering angle tends to align, thus the tire lateral force decreases and, due to the presence of the roll angle, the motorcycle tends to capsize. When the torque is outwards the curve (negative torque) the vehicle is rather stable, because in absence of control the steering angle increases, causing an increment also in the tire lateral force, which brings the motorcycle upright.

This paper focuses on the steering torque exerted by the rider on the handlebars, which is function of many characteristics of the vehicle. The influence of tire characteristics has studied in a previous work[3], in this paper the influence of geometrical and inertial properties of the motorcycle is dealt with. The sensitivity analysis furnishes good guidelines both for the design and setting up processes of motorcycles. An eleven degrees of freedom multi-body model of the motorcycle was developed and applied to simulate the steady-turning conditions. The theoretical results were compared to experimental ones

Mathematical model

The mathematical multi-body model of the motorcycle consists in a system of six rigid bodies connected by kinematic pairs. The six bodies are the following: the rear assembly (with rigidly attached engine, tank and rider), the front assembly (handlebars and sprung fork components), the front and rear wheels, the swinging arm and the unsprung components of the fork. This model has eleven degrees of freedom, as shown in Figure 1: three degrees of freedom are needed to identify the position of the rear frame center of mass, three are associated to the yaw, roll and pitch angles, the remaining are the steering angle, the deflection of the front and rear suspensions and finally the spin angles of both wheels.

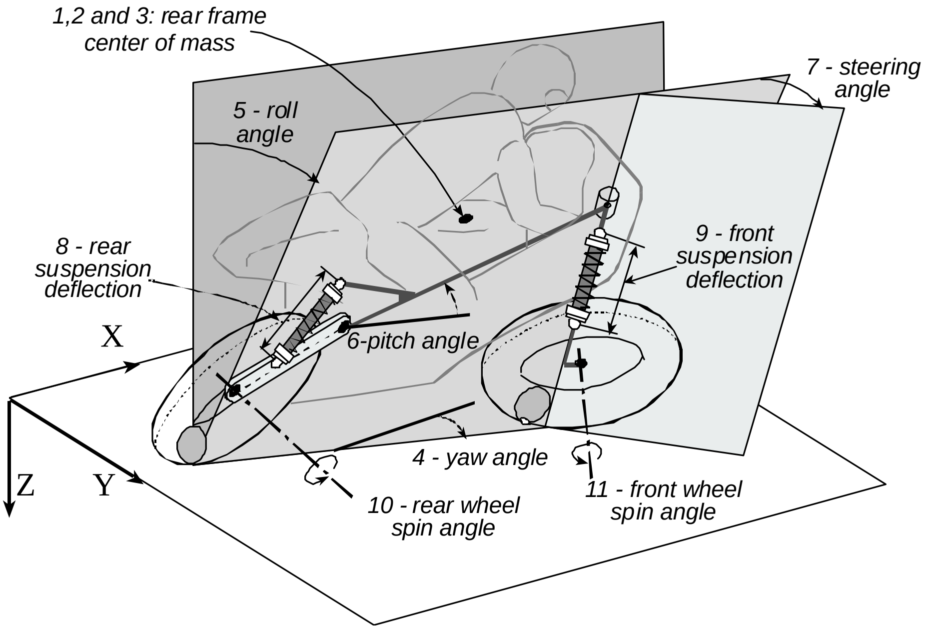

Figure 1 – eleven d.o.f. motorcycle model

The rear suspension force acts between the rear frame and the swinging arm, while the front suspension force acts between the sprung and unsprung components of the fork. Non linear behavior of suspension springs and shock–absorbers is properly modeled. The propulsive engine power is transmitted from the rear frame to the rear wheel by means of the transmission chain. Front and rear brakes are modeled by means of a torque acting between the front wheel and the fork and a torque acting between the rear wheel and the swinging arm respectively. The action of the distributed aerodynamic forces is reduced to a system composed by the drag, lift and lateral forces applied to the rear frame center of mass and by three aerodynamic torques.

The kinematic link between wheels and road is modeled considering the toroidal shape of the tires and their radial deformation. The interaction between each tire and the road is represented by three forces acting at the geometric contact point (vertical load, longitudinal and lateral forces) and by two torques (rolling resistance and yaw torque, while the overturning moment is not considered because the tire force act at the effective contact point)[3,10]. The vertical force is calculated as a function of vertical tire deflection, while the lateral and longitudinal tire forces are calculated as functions of side and longitudinal slips from experimental data using the tire magic formula approach[11,12].

The equations of the motion are derived using Newton-Eulero approach (as explained in detail in reference [3]). Since steady-turning conditions are studied, the equations of the motion are algebraic and their numerical solution has found using the Newton-Raphson algorithm.

Experimental equipment

The experimental steady-turning tests were performed with an Aprilia RSV 1000 motorcycle, which is a high displacement sport motorcycle. It was equipped with a measurement system in order to acquire experimental data descriptive of the steering action of the rider and of the vehicle response. The steering effort of the rider was measured by a custom transducer (shown in Figure 2), which senses the steering torque applied on the handlebars. The handlebars are attached to an additional plate, which is mounted on a bearing: this system leaves the handlebars free to rotate around the steering axis independently from the front frame and wheel. The rotation of the handlebars is transmitted to the wheel through a cantilever, which is fixed to the plate in radial direction and blocked to the fork yokes by means of a custom clamp[5]. When the handlebars are steered, the cantilever is subjected to simple bending, and its deformation is measured by a couple of strain gauges. Two safety stops limit the cantilever deformation range in order to avoid overloading and permit the steer control in case of cantilever rupture.

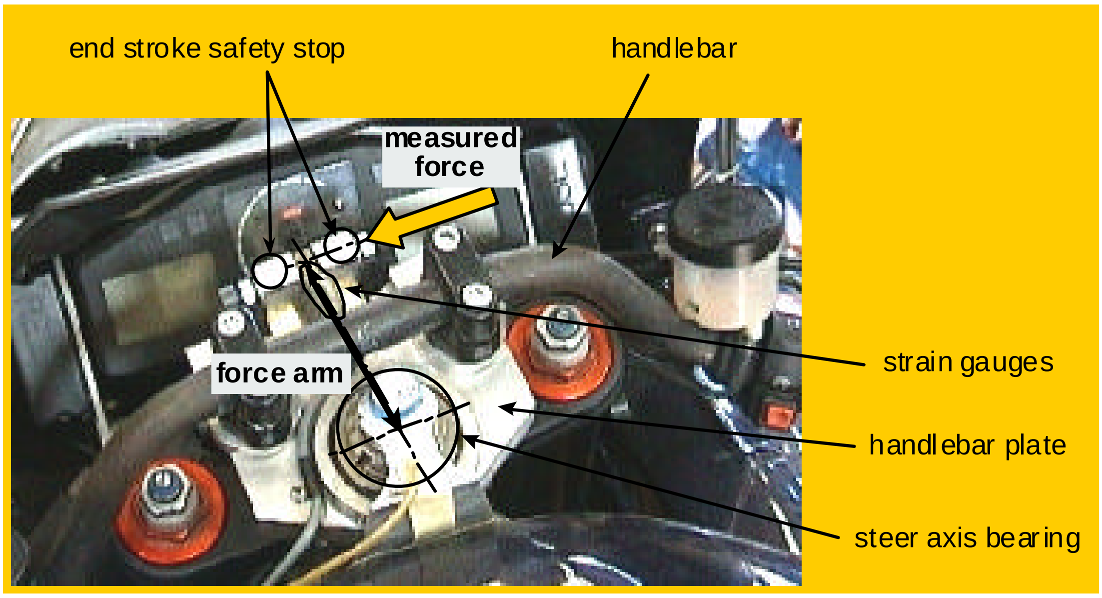

Figure 2 – torque transducer mounted on RSV 1000 Aprilia

The measurement of the roll angle was performed by means of two transducers: a inclinometer and a gyroscope. The inclinometer measures the static roll angle at the beginning and the end of each test (when the motorcycle is still), the gyroscope measures the roll rate and thus permits, by integration, to reconstruct the roll angle time history during the test.

The signals were acquired by a Leane mcdr 128 data recorder which was mounted on the motorcycle. The effect of electrical noise and structural vibration was strongly limited by direct low-pass filtering of the channels.

The experimental results were carried out on steering pads. The acquisitions started with the motorcycle still, then the rider had to start and follow the desired constant-radius lane and complete at least three laps with constant velocity. The signals time history was analyzed and post-processed, obtaining average values of forward speed, yaw rate, roll angle and steering torque.

Theoretical and experimental steady turning steering torque analysis

The theoretical analysis was performed by simulating, with the multi-body code, the behavior of the Aprilia RSV 1000 motorcycle in the steering pad tests. The description of the rider-motorcycle system is given through a very large set of parameters: mass, center of mass position and moment of inertia of the rigid bodies, non-linear elastic and damping characteristics of the suspensions, tire geometry and adherence properties. Inertias and center of mass positions were carefully measured, with custom-built machines[13]. Tires parameters were measured with the rotating disc tire tester machine[14], which has been developed at Dept. of Mechanical Engineering of Padova University (DIM). Driver’s inertia properties were estimated with static measurements and compared with other previous results found in literature[15].

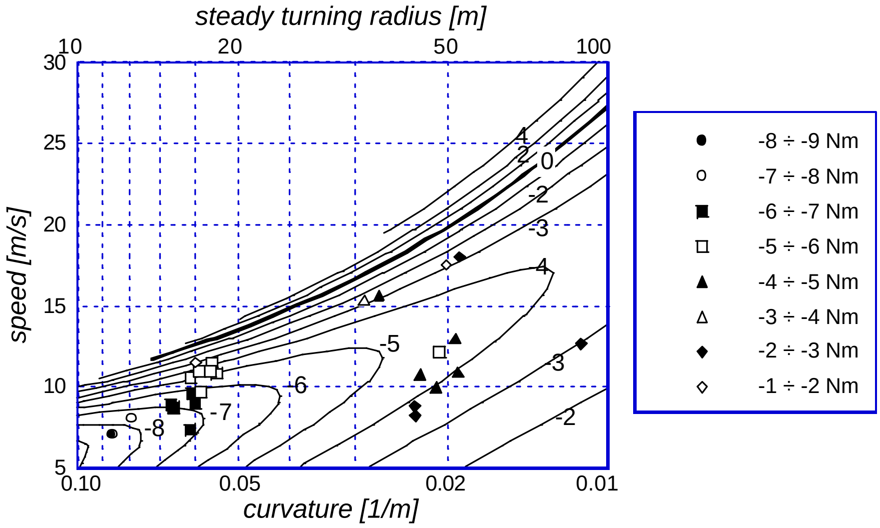

Figure 3 – comparison between calculated and measured steering torque versus forward speed and turning radius

The experimental tests were carried out with forward velocities in the range 6-20 m/s and steady turning radii in the range 15-50 m. The same ranges of speeds and radii were simulated with the multi-body code.

The steering torque is represented as a function of path curvature and forward speed, and the simulated results are compared with the experimental ones in Figure 3. Theoretical results are presented with contour plot, experimental ones with spots. It is worth observing that the maximum speed that can be kept on a certain radius is a growing function of the radius and of the tires performance, as can be seen moving upwards along a vertical (constant radius) line. On the plot, the maximum lateral acceleration values reach the gravity acceleration.

The agreement between simulated and experimental data is good. Both experimental and simulated results show that, with a fixed turning radius, if the velocity is increased the steering torque decreases until a minimum, then it increases and it can reach positive values when the speed is high. It is worth underlining that the steering torque is nearly always negative, both in experimental and simulated results. This means that the stability conditions of the capsize mode cover the majority of the real conditions, except for the high-speed (or high-lateral acceleration) turns. The graph shows that the ideal conditions, in which the steering torque has zero or slight negative values, is still a function of curvature and speed. In particular, when the turning radius increases, the ideal speed range shifts to larger values.

The influence of motorcycle geometry and inertia on the steering torque

The steady turning behavior of a motorcycle is a function of vehicle geometry, inertia and tire properties. The effect of tire properties has been highlighted in a previous paper[3], so in this paper the influence of vehicle characteristics on the steering torque is studied.

Once the multi-body code had been validated with experimental data, the sensitivity analysis of the steering behavior was carried out by means of the numerical simulations. The Figure 4 shows the vehicle parameters that are studied.

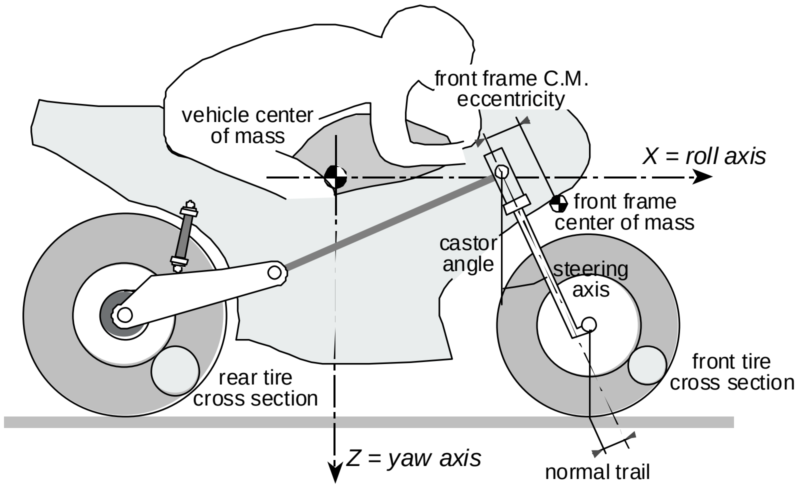

Figure 4 – geometrical and inertial parameter taken into account in sensitivity analysis

First, the influence of the geometrical parameters is dealt with. The Figure 5a shows the reference case, while Figure 5b shows the effect of an increment in the normal trail: the steering torque contour plot shift towards lower values in the whole domain considered, while no significant change in the shape of the curves. This result can be explained considering that when the trail increases, the self-steering effect due to the front tire vertical load increases more then the aligning effect do to the lateral force. The result is a more stable steering behavior, in the domain of interest.

On the contrary, increasing the castor angle (Figure 5c) causes an aligning effect, since the steering torque increases (as it has negative values, its magnitude decreases). It is worth noting that the effect of the castor angle is pronounced. Considering that the real castor angle is influenced by motorcycle’s attitude, depending on the speed, mass distribution and suspension behavior, particular attention has to be paid to this parameter.

The front tire head radius increment has a strong aligning influence (Figure 5d): this effect is caused by the displacement of the front wheel contact point due to the roll angle. It can be seen that the zero steering torque curve shifts towards lower values of the forward speed, and the resulting behavior is quite different from the reference case.

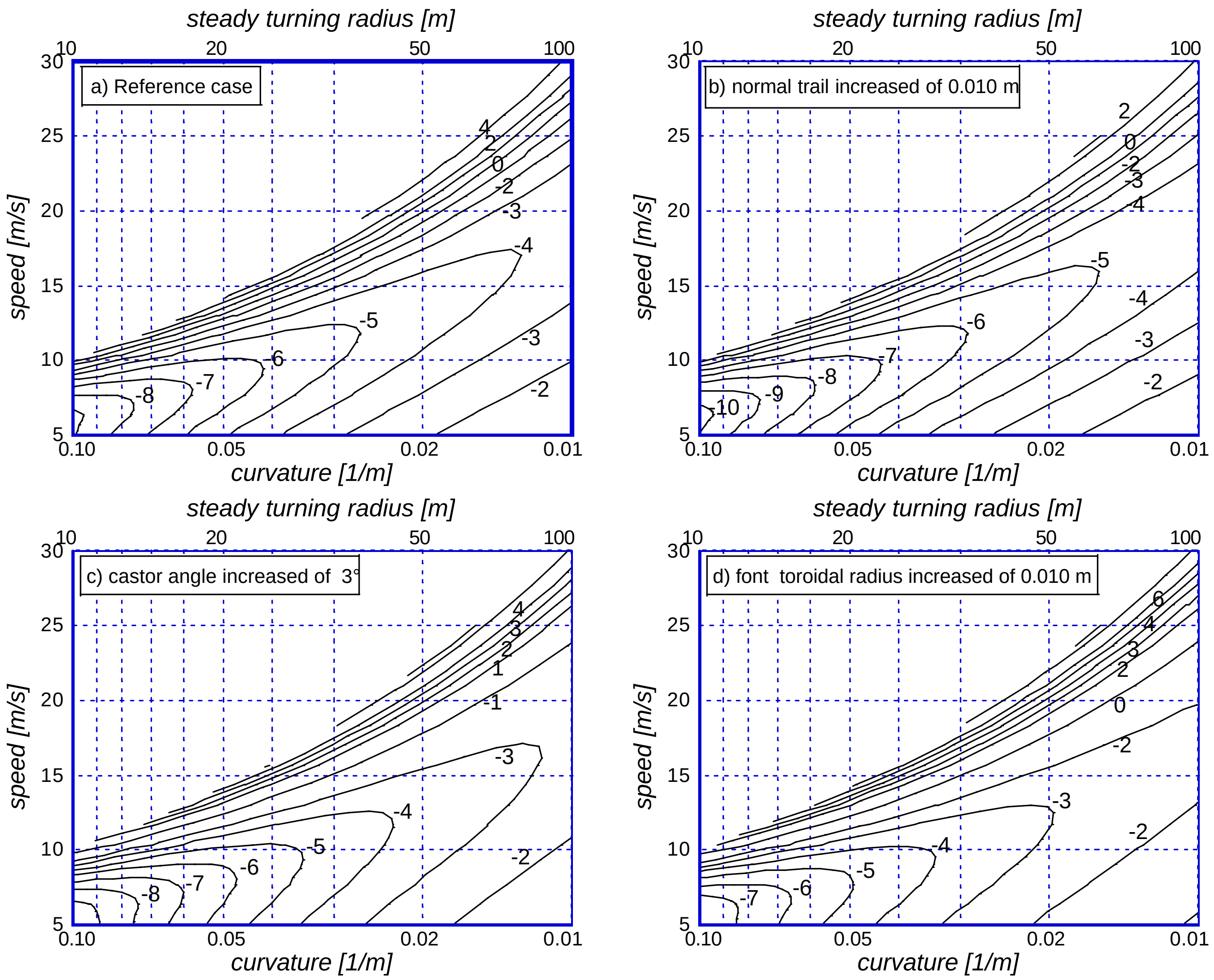

Figure 5 – influence of some geometric characteristics on the steering torque

The influence of inertial characteristics of the vehicle-rider system is then analyzed (Figure 6). In all the examined cases the shape of contour plots is similar, but steering torque values are rather different.

Figure 6b shows the effect of front wheel gyroscopic moment. Increasing the front wheel axial moment of inertia causes an aligning effect on the steering torque, since it tends to raise its values.

A forward displacement of the rider's center of mass (Figure 6c) has a slight self-steering effect. The vertical position of the rider's center of mass has a very small aligning effect, and for this reason it is not represented. The result is that if the rider moves remaining in the plane of symmetry of the motorcycle the steering behavior doesn't change. On the contrary, a rider lateral displacement inward the curve (Figure 6d) has a strong aligning effect. Considering that the sport riders usually move laterally very much, the steering characteristics of the motorcycle are strongly modified by the driving style[5]. An expert rider can take advantage of this possibility to shift the low steering torque zone to the instantaneous steering conditions and thus better control the steer.

The presence of a passenger alters mass distribution of the motorcycle. The resulting effect (Figure 6e) is slightly aligning, but the steady turning steering torque is not substantially changed.

Finally, the influence of eccentricity of front frame center of mass is shown in Figure 6e. A larger eccentricity causes an increase both in the inertia torque, which is aligning, and in gravity torque, which is self steering. This second effect is larger and the result is a self steering effect, that is highlighted by lower values of the steering torque.

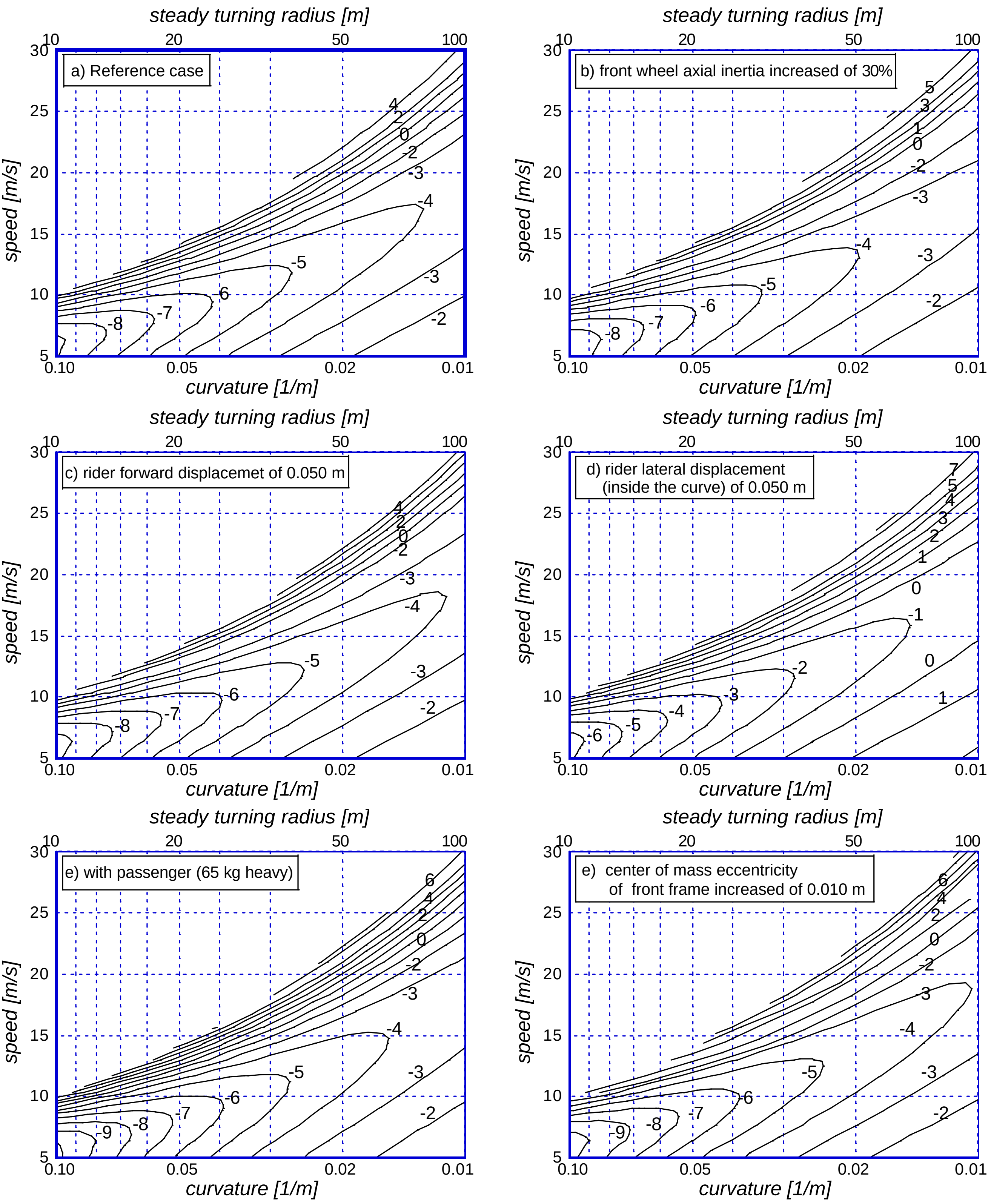

Figure 6 - influence of some inertial properties on the steering torque

Table 1 summarizes the exposed results considering a 50 m radius curve, covered at 15 m/s forward speed (which corresponds to a lateral acceleration of 4.5m/s^2 and to a roll angle of about 30°). The parameters are sorted with respect to their influence on the steering torque: first the parameters that cause aligning effects, then the parameters that cause self steering effects.

Table 1 – steering torque in steady turning (15m/s speed and 50m radius)

Motorcycle characteristics	steering torque [Nm]	steering torque variation [Nm]	
rider lateral position moved 0.050 m toward the center of the curve	-1.23	3.10	**aligning effect**
front tire cross diameter increased of 0.010 m	-2.31	2.02	
castor angle increased of 3°	-3.19	1.13	
front wheel axial inertia increased of 30% (0.14 kgm^2)	-3.70	0.62	
with passenger 65 kg heavy	-3.95	0.38	
motorcycle center of mass lowered of 0.020 m	-4.00	0.32	
reference case	**-4.33**	0	
motorcycle center of mass moved 0.020 m forward	-4.53	-0.21	**self steering effect**
eccentricity of front frame center of mass increased of 0.010 m	-4.55	-0.22	
rear tire cross diameter increased of 0.010 m	-4.96	-0.63	
normal trail increased of 0.010 m	-5.23	-0.91	

The influence of motorcycle geometry and inertia in the transient

Steady state motorcycle behavior can give only basic information about vehicle handling and stability. More detailed information can be derived from dynamic simulation. For this purpose, some dynamic simulations has been carried out using a multibody code, studying the transition from straight line running to steady state cornering (speed is 15m/s, cornering radius 50m).

A 11 d.o.f. multibody model, which has been developed at DIM (to be published), has been used for these simulation. To validate this code, some simulations results has been compared to those obtained by means of commercial package Visual Nastran, an excellent agreement was found. Moreover, some simulations related to steady state cornering has been compared to the simulations carried out with the steady state model (described in previous section), finding complete agreement.

It is impossible to carry out open loop simulations due to the intrinsic instability of two wheels vehicles and it is necessary to define a rider model, which must be capable at least stabilizing the lateral motion of the motorcycle. This implies another problem: it becomes very difficult to distinguish between properties that are related to the motorcycle and properties that are related to the rider model. For this reason, the following very simple PID controller on rider steering torque has been used (it has only the purpose of stabilizing the vehicle and following the desired roll angle):

$$\tau = -120(\varphi_d - \varphi) + 30\dot{\varphi} + 40\int_0^t (\varphi_d - \varphi)\,d\bar{t}$$

where φ is the effective roll angle, φ_D is the desired roll angle and τ is the steering torque. The desired roll angle is a cosine ramp from zero to maximum roll angle equal to 0.5 rad.

Figure 7 and Figure 8 show the behavior of the steering torque and the roll angle during the manoeuvre, some geometrical parameters of the motorcycle in Figure 7 and some inertial parameters in are varied in Figure 8. The figures show that both roll angle and steering torque start from zero (straight line running condition), then the rider steers outwards to the curve (negative steering torque) and the motorcycle capsizes inwards to the curve (positive roll angle). As roll angle and roll rate increase, steering torque exerted by the rider after a minimum tends to the steady state value, that in this case is negative (outwards to the curve).

On Figure 7a, the comparison between the reference case (dotted line) and the vehicle with an increased castor angle (solid line) shows that the magnitude of the steady state torque in the second case is lower than in the first case, while the negative peak torque in the second case is greater than in the first case**.** Figure 7b compares the reference case to the vehicle with an increased normal trail (solid line). In this case, both in steady state and transient condition the magnitude of steering torque is greater for the second vehicle than for the first one.

Figure 8a compares the reference case to the vehicle with an increased yaw moment of inertia (solid line). The steady state steering torque is the same in both cases as expected, because the yaw moment of inertia does not influence motorcycle equilibrium in the steady turning. Anyway, during the transient the vehicle that has major inertia requires a greater steering torque, even if the differences are very small because in this simulation the yaw acceleration is small.

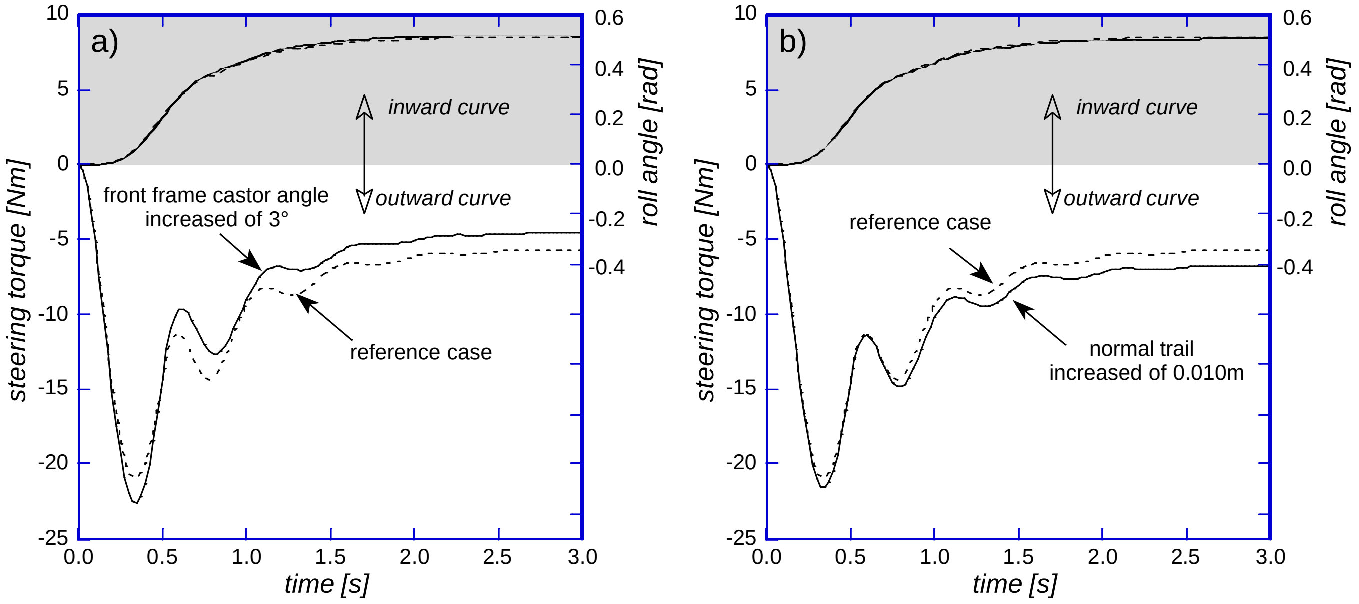

Figure 7 - influence of castor angle and normal trail on transient steering torque

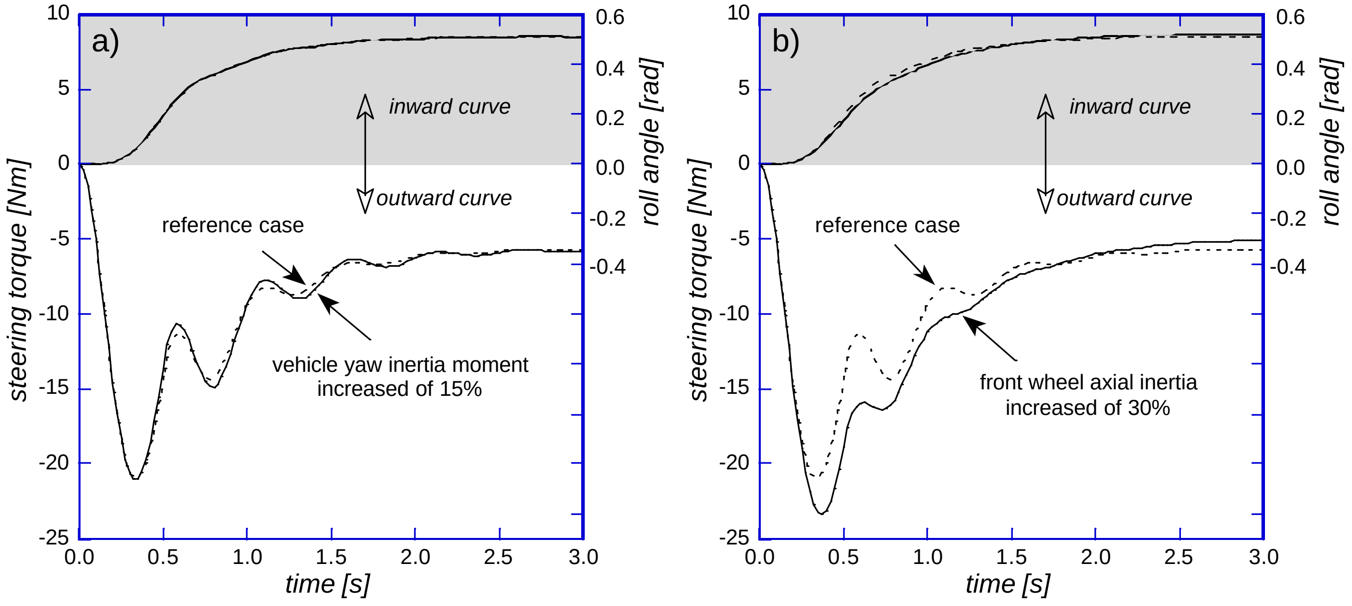

Figure 8 - influence of frame moment inertia respect to the yaw axis and front wheel axial inertia on transient steering torque

Figure 8b compare the reference case to the vehicle having an increased axial moment of inertia of front wheel (solid line). In steady state steering the gyroscopic effect due to the front wheel spinning causes small reduction of the steering torque magnitude, while during the transient the stabilizing gyroscopic effect requires a remarkable increment of the steering torque magnitude, but the torque applied is more regular then in the reference case.

Conclusion

The cornering manoeuvre has been analyzed both in the steady state and the transient condition. Steady state analysis has been carried out both with experimental tests and numerical simulations. Agreement between simulations and experimental data allows to validate the multi-body model. Then, the multi-body model is used for sensitivity analysis in steady state cornering and for dynamic simulations.

Steering torque in steady cornering has been represented by contour plots, as a function of path curvature and forward velocity. Sensitivity analysis concerns the variation of some geometric and inertial vehicle properties. Results shows that the rider lateral position and castor angle have a strong influence on the steering torque, while other parameters have a smaller influence. If result of previous analysis[4] are considered, it can be stated that the influence of tire properties is bigger then influence of most geometric and inertia vehicle properties.

The transition from straight running to steady turning has been analyzed by means of dynamic simulations. Because of the intrinsic instability of the motorcycle, a stabilizing control system was required. Simulations show that the vehicle properties can influence dynamic behavior in a different manner than they influence steady state motion. In particular, the wheels axial inertia and the vehicle's yaw moment of inertia have more importance during the transient than in steady state.

References

[1] Weir, D.H. and Zellner, J.W.: *Development of Handling Test Procedures for Motorcycles*. SAE paper 780313, 1978.

[2] Riedl, K. and Lugner, P.: *Naehere Untersuchungen zur stationaren Kurvenfahrt von Einspurfahrzeugen*. Vehicle System Dynamics 11 (1982), pp. 175-193.

[3] V. Cossalter, A. Doria, R. Lot: *Steady Turning Of Two Wheel Vehicles*, Vehicle System Dynamics, 1999.

[4] A. Doria, M. Da Lio, R. Lot: *The Steering Behavior Of Motorcycles*, EAEC II Conference Vehicle Dynamics and active safety, Barcelona 1999.

[5] D. Bortoluzzi, A.Doria, R. Lot, L. Fabbri: *Experimental Investigation And Simulation Of Motorcycle Turning Performance,* 3rd International Motorradkonferenzen, Monaco 2000.

[6] Ishii, H. and Tezuka, Y.: *Considerations of Turning Performance for Motorcycles*. JSAE paper 9734601, SAE paper 972127, 1997.

[7] A. Aoki: *Experimental Study on Motorcycle Steering Performance*, SAE paper 790265, 1979.

[8] V. Cossalter, M. Da Lio, F. Biral , L.Fabbri, *Evaluation of Motorcycle Manoeuvrability with the Optimal Manoeuvre Method*, SAE Meeting;1998 Motorsports Engineering Conference&Exposition, Dearborn, Michigan, 16-19 november 1998

[9] V. Cossalter, M. Da Lio, R. Lot, L. Fabbri: *A General method for Evaluation of Vehicle Manoeuvrabilty with Special Emphasis on Motorcycles* , Vehicle System Dynamics, 1999.

[10] R. Berritta, V. Cossalter, A. Doria, R. Lot, *Implementation of a motorcycle tire model in a multi-body code* , Tire Technology International, UK&International Press, United Kingdom, march 1999.

[11] H.B. Pacejka and R.S. Sharp: *Shear Force Development by Pneumatic Tyres in Steady State Conditions: A Review of Modelling Aspects.* Vehicle System Dynamics 20 (1991), pp. 121-176.

[12] H.B. Pacejka and E. Bakker: *The Magic Formula Tyre Model*. Vehicle System Dynamics Supplement 21 (1991), pp. 1-18.

[13] M. Da Lio, A. Doria, R. Lot: *A Spatial Mechanism for the Measurement of the Inertia Tensor: Theory and Experimental Results*, ASME Journal of Dynamic Systems, Measurement and Control, march 1999.

[14] V. Cossalter, A. Doria, R. Berritta: *Identification of the lateral and cornering stiffness of scooter tyres using impedance measurements*, the 2nd International Conference on Identification in Engineering Systems, Swansea, 28-31 march,1999.

[15] Bartlett, R.: *Introduction to Sports Biomechanics* -E & FN Spon- London, 1997.

Acknowledgements

The authors are grateful to Prof. V.Cossalter and Dr. A. Doria for his advice and encouragement.

This research was partially supported by funds from the Italian Ministry for Universities and for Scientific and Technological Research (MURST 40% funds)