Analisi sperimentale della maneggevolezza di un veicolo rollante a tre ruote.

P. Agostinetti, V. Cossalter, N. Ruffo
Dipartimento di Ingegneria Meccanica, Università degli Studi di Padova

Experimental analysis of handling of a three wheeled vehicle

P. Agostinetti, V. Cossalter, N. Ruffo
Department of Mechanical Engineering, University of Padua

ABSTRACT

This paper focuses on handling performances of an innovative three-wheeled vehicle. A three-wheeled vehicle is a fine synthesis between the manoeuvrability and compactness of a motorcycle and the stability and load-bearing capacity of a four-wheeled car.
The vehicle presented in this paper is characterized by an innovative rolling system. The front frame is connected to the rear frame by means of a four bar linkage that makes it possible the tilting of front frame like motorcycles while the rear frame does not tilt. The linking system geometry can be adjusted to set the position of the instant tilting axis of the front frame with respect to the rear one closer to or further from the road surface.
An experimental investigation was carried out using a real working prototype that was built at the Department of Mechanical Engineering, University of Padua, in collaboration with Aprilia Spa. The prototype can change the geometry of the linking system. Moreover this vehicle was equipped with a measurement system in order to acquire experimental data. Different test drivers have accomplished slalom manoeuvres with different geometrical configurations. These tests permit to evaluate the handling properties of the different configurations of the vehicle.
A new index for handling evaluations is proposed.

1. INTRODUCTION

Looking at motorcycle magazines you can notice the absence of a handling index. You can find indexes like maximum speed, acceleration, maximum power and torque of any model but there is not a index that you can use both to compare and to quantify the motorcycle handling.
From the other side, the handling is often explained by the test-drivers. They talk in terms of aptitude for roll, easy drive, aptitude to get in the curve, safety feeling, etc.
The experimental research on this argument started since 1970’s when we started to consider the handling concept and the manoeuvrability concept for the motorcycle. We define a vehicle handy, when it is easy to drive. This involves the driver’s judgement, who may find different vehicles more or less easy to ride. On the other hand, the manoeuvrability is the ability of a vehicle to complete a given manoeuvres as fast as possible without to exceeding physical limitations, like tyre adherence but without considering the physical and mental pilot effort [1].
It is evident that a good manoeuvrability is a necessary condition, but not sufficient to have also good handling behaviours.
This paper focuses on handling performances of an innovative rolling three wheeled vehicle. It is characterized by a particular adjustable rolling system that makes it possible to change the position of the instant tilting axis.
An experimental investigation was carried out using a real working prototype. Moreover this vehicle was equipped with a data acquisition system in order to acquire the steering torque applied by the rider and the most important dynamic and cinematic quantities. Different test drivers have accomplished slalom manoeuvres with different geometrical configurations of the vehicle.
These tests permitted both to evaluate the handling properties different geometrical configurations of the vehicle and to find a new handling index.

2. VEHICLE DESCRIPTION

A model of this vehicle was developed [2, 3] using a multi-body program (Fig. 1). Many analyses have been carried out varying the geometrical parameters of the linking system in order to highlight the properties of manoeuvrability and stability of this novel vehicle.
In order to study the characteristic of handling, a real working prototype (Fig. 2) was built at the Department of Mechanical Engineering [4], University of Padua, in collaboration with Aprilia S.p.A. .
The vehicle is characterized by an innovative system that connect the front frame to the rear frame by means of four bars linkage (Fig. 3) that makes it possible the tilting of front frame, like normal motorcycles, while the rear frame does

not tilt. The linking system geometry can be adjusted to set the position of the instant tilting axis of the front frame with respect to the rear one closer to or further from the road surface.

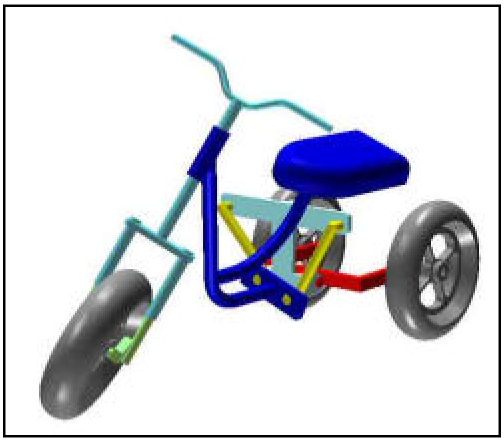

Fig. 1 Virtual Model

Fig. 2 Prototipe

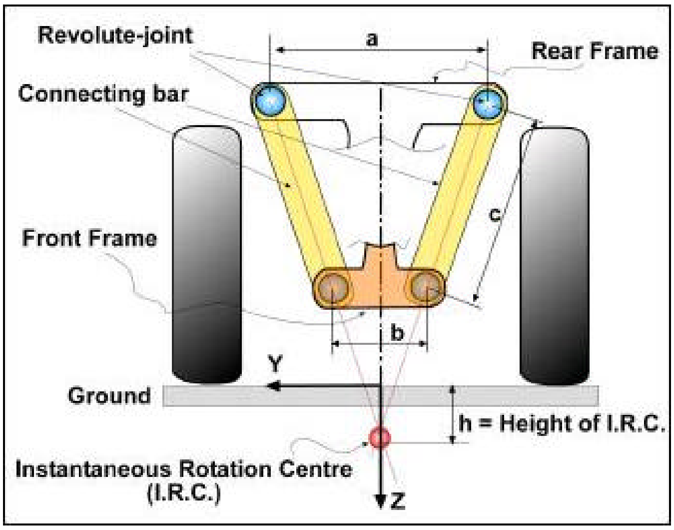

Fig. 3 Four bars linkage elements.

The four-bars linkage is made up of the rear frame – fixed to the bar ***a*** - which doesn't tilt, the tilting front frame – fixed to the bar ***b*** - and two connecting bars ***c*** that link the front and rear frame by means of four revolute-joints, which have the same axis orientation.
With this configuration the front frame rotates around an instantaneous tilting axis.
The intersection of the tilting axis with the four bar linkage plane defines the instantaneous rotation centre (referred to as *i.r.c.*). The *i.r.c.* position in the linkage plane is defined by the intersection of the two axes of the connecting rod, as shown in Fig.3.
Hence, the distance ***a*** between the two superior revolute-joints, the length ***c*** of the connecting bars and the distance ***b*** between the two inferior revolute-joints define the instantaneous rotation centre position. Height ***h*** is defined as the vertical distance between road plane and i.r.c.; its value is positive when the *i.r.c.* is above the road plane, negative if the *i.r.c.* is below the road plane. The instantaneous tilting axis can be moved up and down with respect to the road surface by decreasing or increasing the distance between the revolute-joints (parameters ***a*** and ***b***).
They were chosen three different configurations of the tilting system to carry out the tests. Passing through configuration I to configuration III, the vehicle becomes more handy (Fig. 4) as the tests result will show.

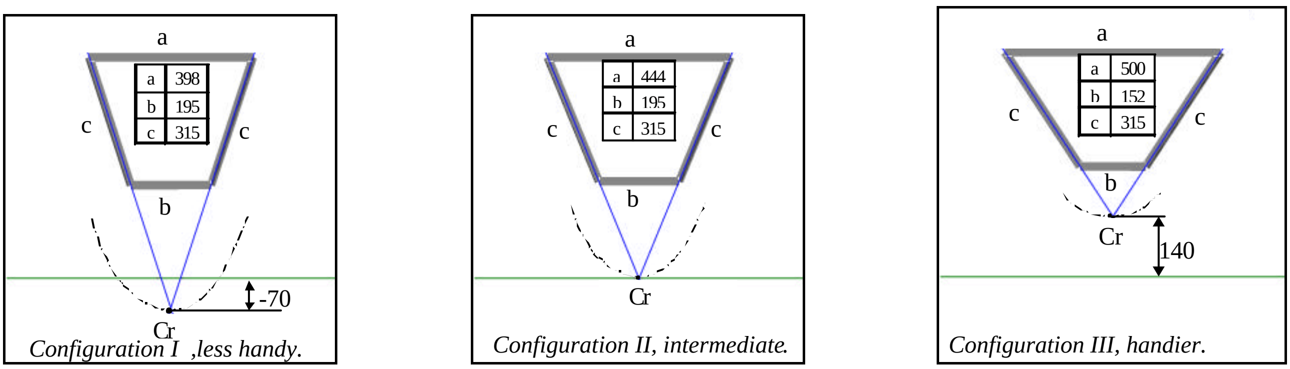

Fig. 4 Configurations tested (distances expressed in mm).

As well known another element that influence very much the motorcycle handling is the front tire. That's why we decided to carry out other tests with different front tire. The following table shows the characteristics of the tires that were used in the test.

Tire	Brand	Model	Size	Outside radius	Overall width
A	Bridgestone	Hoop-B02	150/70 MC 13	270 mm	105 mm
B	Sava	MC 16	130/60 MC 13	238 mm	78 mm

Tab. 1. Tires tested

It is interesting to notice that passing from tire A to tire B, the outside radius decreases of 12%, while the overall width decreases of 26 %, the front-end inertia and mass decrease and the vehicle's center of mass decreases lightly.

3. DATA ACQUISITION SYSTEM

The vehicle was equipped with a measurement system in order to acquire experimental data on kinematic and dynamic quantities descriptive of the behavior of the vehicle. Measured kinematic quantities and transducers are listed in table 2.

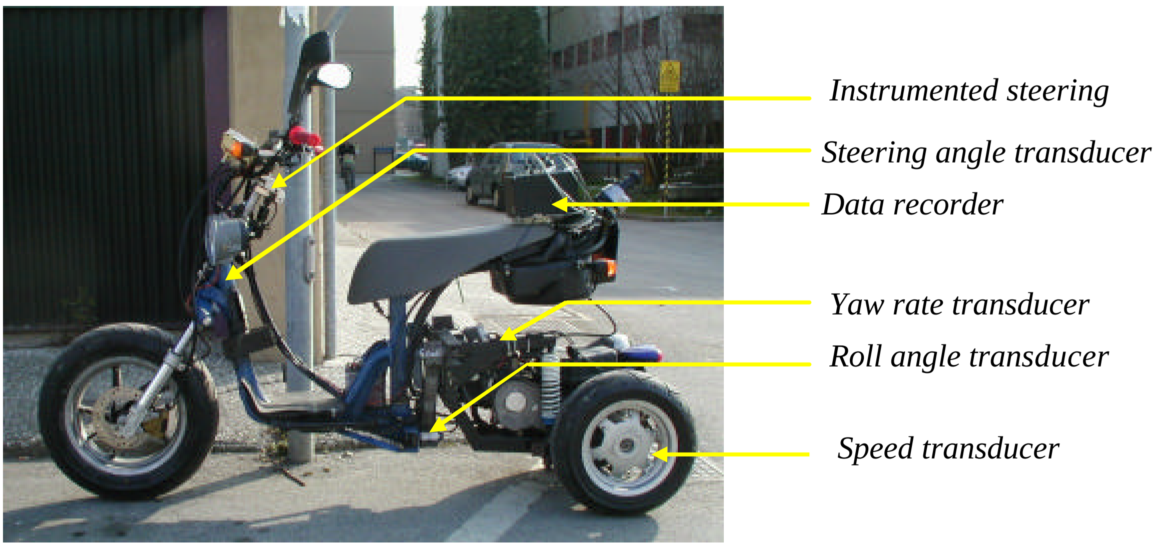

Fig. 5 Data acquisition system

Kinematic quantity	Transducer	Type
Torque	Custom-built	Strain gauges
Steering angle	Rotational potentiometer	Sensor Pot Novotechnik
Roll angle	Rotational potentiometer	Sensor Pot Novotechnik
Yaw rate	Single axis gyroscope	British Aerospace 299641-0100
Velocity	Proximity transducer	BLT DSA8/5608KS
Data recorder: Leane MCRD-128 -sampling rate 100 Hz-		

Table 2: Measured quantities and transducers

The measured dynamic quantity is the steering torque applied by the rider to the handle-bars. A custom-built transducer (Fig.6) had to be developed to measure the steering torque.

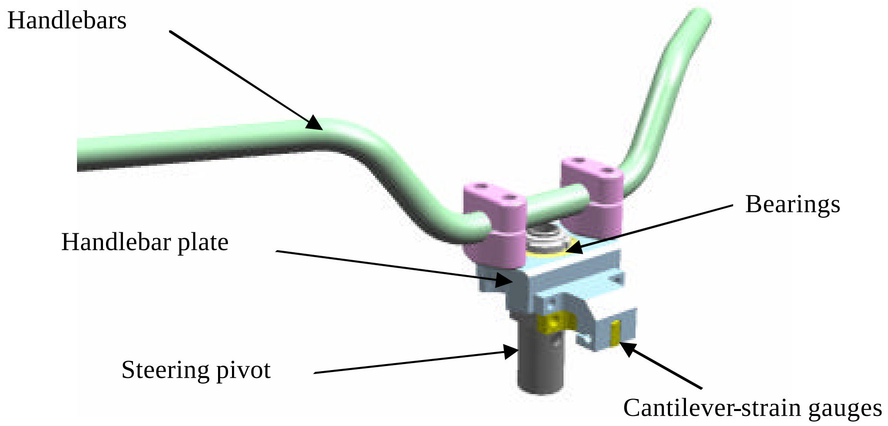

Fig. 6 Steering torque transducer

The handlebars are fixed to a plate, which is mounted on a bearing that leaves it free to rotate around the steering axis independently from the front frame and the front wheel. The rotation of the handlebars is transmitted to the front frame through a cantilever fixed to steering pivot and blocked on the handlebars-plate by a custom clamp. Two strain gauges in half bridge configuration are mounted on the cantilever and measure its flexural deformation, which is proportional to the force applied. The steering torque is thus proportional to the force by means of the arm.

4. SLALOM TESTS

The experiments consisted of slalom tests at different combinations of speeds and spacing of cones.
Each single test was carried out with constant spacing among cones and constant velocity. In this way the main state variables vary in a fairly sinusoidal fashion, and the most prominent signal frequency is that at which the cones are encountered during the slalom, that is:

$$f = \frac{u}{2 * p}$$

where ***u*** is forward velocity and ***p*** cone spacing.
In particular, they were chosen spacing of 3, 5, 7, 9, 11, 13, 14 meters.
The roll angle was obtained from the measured angle at the inferior revolute-joints between the two bars ***b*** and ***c*** of the mechanic tilting system, calculating the rotation of the bar ***b*** –front frame - with respect to de bar ***a*** – rear frame -.
The roll rate was obtained by numerical derivation of roll angle, while the yaw angle was obtained by numerical integration of the measured yaw rate, without take into account of the roll angle because, fortunately, we could fix the yaw gyroscope on the rear frame that does not tilt.
Figure 8 shows an example of the acquired raw data corresponding to ‘steady-state’ slaloming at constant velocity that was retained for post-processing and analyzed.
Observing Fig. 8 we can see that, performing the 7m-step slalom at 0.5 Hz, the driver has to apply larger steering angle δ, larger roll angle φ, larger yaw angle ψ and smaller steering torque than in the 14m-step slalom at the same frequency of 0.5Hz.

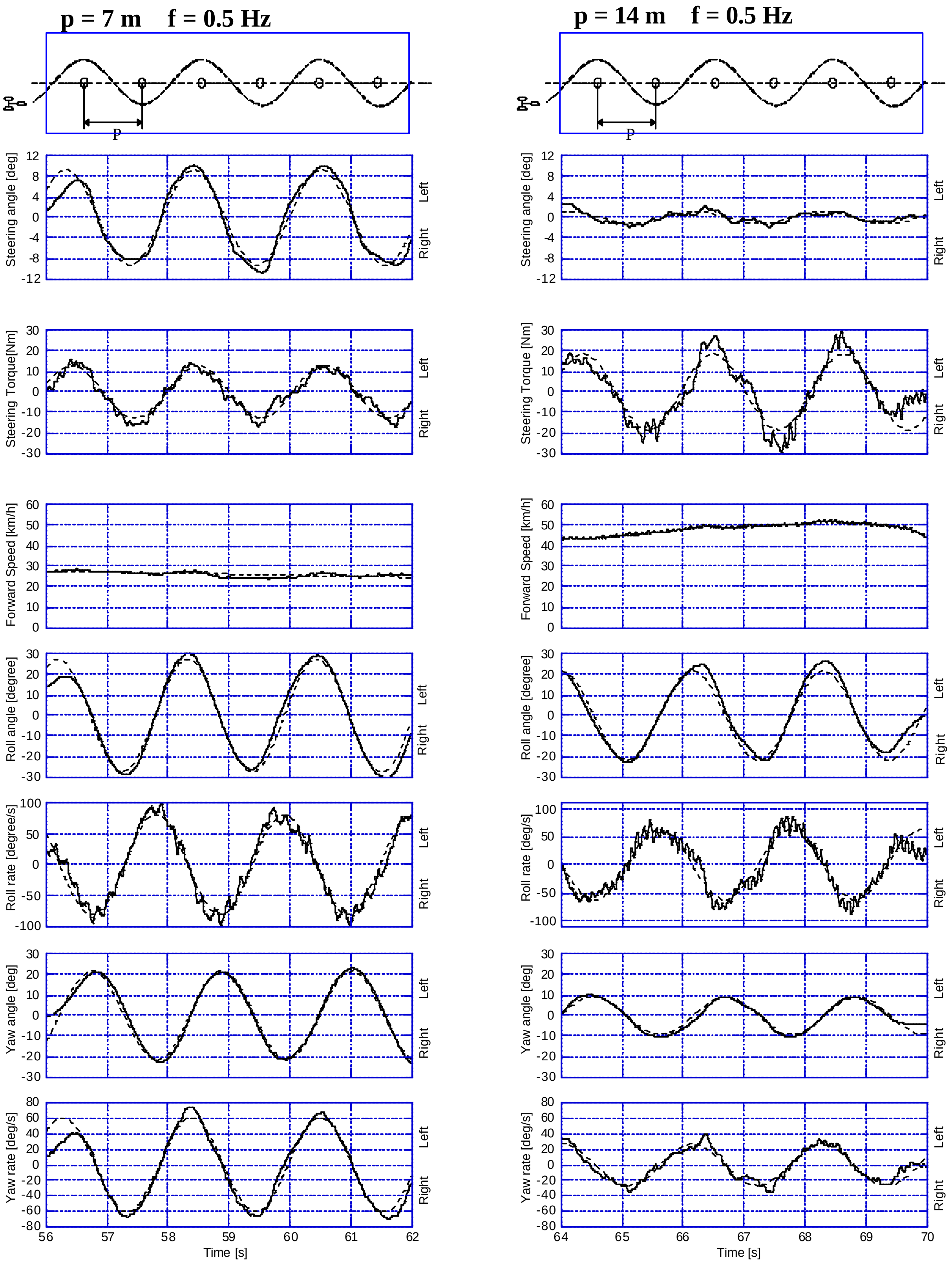

Fig. 7 Acquired data, cones spacing 7 and 14 m, frequency 0.5 Hz

5. SIGNIFICATIVE PARAMETERS

Some significative parameters, that we will consider and compare in each test, are:

Measured parameters:

1. Steering angle δ
2. Steering torque τ
3. Roll angle φ
4. Yaw angle ψ

Calculated parameters:

5. Specific roll (φ/τ): This ratio gives an information about the reaction of the steering gear; if it is low it means that it is necessary to apply a great torque to obtain a given roll angle.
6. Phase-displacement φ-τ: This quantity shows the advance of the steering torque in respect to corresponding roll angle. As exemplified in Fig. 8, we consider advance between this two signals, the time gap between a peak of τ and the corresponding peak of φ (which is by the other side because a right-side torque in a motorcycle generates a left-side roll angle). Phase-displacement is calculated like: $\frac{\text{advance}}{\text{period}} \cdot 360°$

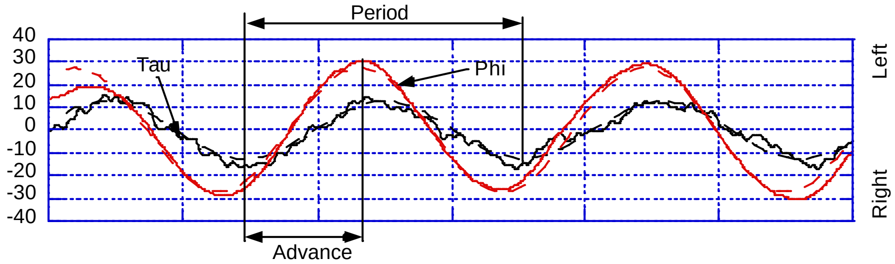

Fig. 8 Phase-displacement between j and t: example of a 7m-step slalom

7. Steering efficiency ($E_1=\varphi/\delta$): This ratio shows how much the imposition of a steering angle gives rise to a roll angle.
8. Roll efficiency ($E_2=\psi'/\varphi$): This ratio shows how much the imposition of a roll angle gives rise to a yaw rate.

6. COMPARATIVE OF CALCULATED PARAMETERS

The tests pointed out the influence of these three factors to the significative parameters:

1. Slalom execution frequency.
2. Configuration of articulated quadrilateral (and consequently height of roll centre). We made tests in both slaloms using configurations I, II and III: in this way we pointed out the difference of the dynamic behaviour with different configurations of the articulated quadrilateral (without changing the path). The front tyre used in these tests is always tire A.
3. Diameter of front tyre. We made tests in both slaloms using the two different front-tyres. In this way we pointed out handling variations obtained by changing front-tyre (without changing path). The configuration of the articulated quadrilateral in these tests is always the II (intermediate).

To valuate the influence of these three factors, we report, in comparative graphs, significative parameters in function of frequency. As an example, in Figs. 9 and 10 are showed graphs concerning the 14m-step slalom in which we compare significative parameters 5 and 6 (specific roll φ/τ and phase-displacement between τ and φ) varying the configuration of the articulated quadrilateral. In Figs. 11 and 12, we study the variation of the same two parameters (5 and 6) with the variation of tyre diameter (again in the 14m-step slalom). On the right side of each graph there is a remark about the influence of the two factors.

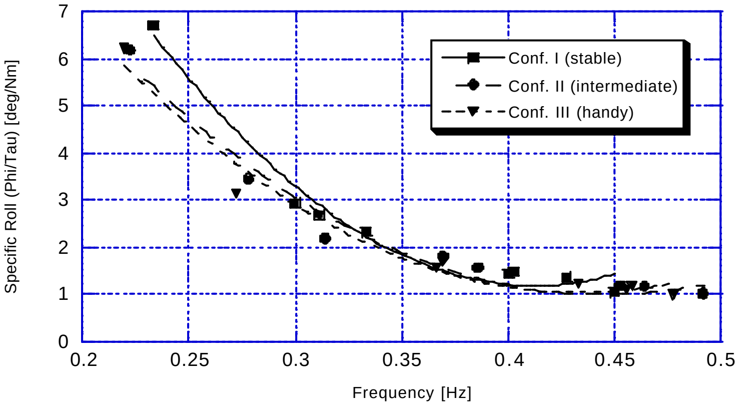

Fig. 9 Specific roll with the three configurations of the quadrilateral in 14m-step slalom

Influence of configuration:
The three configurations have specific roll slightly different at low frequencies. They're in decreasing order I, II, III. Conf. I has a higher ratio φ/τ, which means that the pilot has to apply a smaller torque to gain a certain roll angle. At high frequencies, this effect disappears.

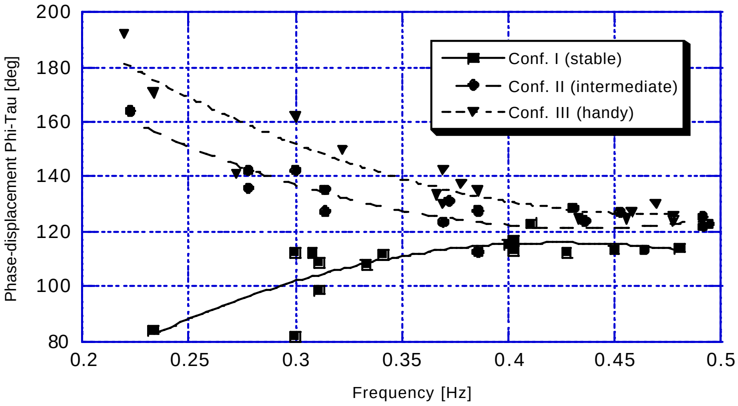

Fig. 10 Phase-displacement j-t with the three configurations of the quadrilateral in 14m-step slalom

Influence of configuration:
The three configurations have phase-displacement in decreasing order III,II,I. Conf. I needs a lower advance of τ in respect to φ. This effect is stronger at low frequency. We can observe that phase-displacement tends to about 120° increasing the frequency, in all the configurations.

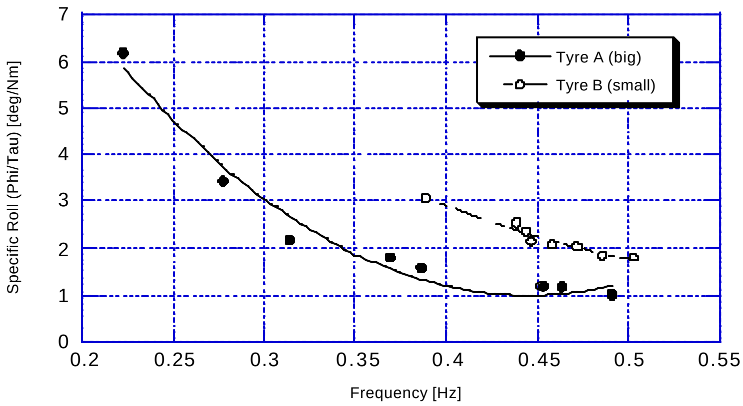

Fig. 11 Specific roll with the two front-tyres in 14m-step slalom

Influence of front-tyre diameter:
Specific roll is about 1°/Nm higher with tyre B instead of tyre A. This means that the pilot has to apply a smaller torque to gain a certain roll, if there is the smaller front-tyre.

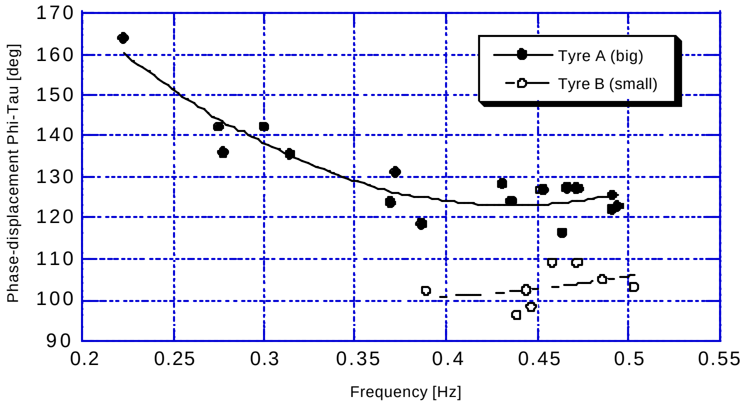

Fig. 12. Phase-displacement j-t with the two front-tyres in 14m-step slalom

Influence of front-tyre diameter:
Driving the scooter with the smaller tyre, the pilot has to anticipate less the steering torque τ in respect to the corresponding roll angle φ. The difference between the two conditions is about 25°

We retain that exists an influence of the configuration of the articulated quadrilateral to a significant parameter if the three interpolating curves are ordered in direction I, II, III or vice versa from top to bottom of the graph. For example in Fig. 10 we can note that quadrilateral configuration influences parameter 6 (especially at low frequency).
Analogously, we think that exists an influence of front-tyre to a significant parameter if the two interpolating curves are ordered in direction 1,2 or vice versa from top to bottom of the graph. For example, in Fig. 15 we can see that the front-tyre diameter influences parameter 5.
We decided to make deeper our study on two slalom 7 and 14 m. We noted that in the both two slaloms the influence of quadrilateral configuration and tyre model was qualitatively the same. For example, in both slaloms if we used the tyre B instead of the tire A, the specific roll is higher.
So we can trace a synthesis diagram like the below one that contains qualitative information (it sums up the tests made in both slaloms), it's still very interesting.

Increasing of slalom frequency *[without changing configuration and tire]*.

1. Decrease of δ
2. Increase of τ
3. Increase of φ
4. *No influence to y*
5. Decrease of φ/τ
6. Phase-displ. τ-φ tends to α
7. Increase of φ/δ
8. Decrease of ψ'/φ

Lowering of roll centre passing from conf. III to conf. I *[without changing factors frequency and tire]*.

1. Increase of δ
2. *No influence to t*
3. *No influence to j*
4. Increase of ψ
5. Increase of φ/τ
6. Decrease of phase-displ. τ-φ
7. *No influence to j/d*
8. *No influence to y'/j*

Increasing of front-tyre diameter passing from tyre B to tyre A *[without changing frequency and configuration]*

1. Increase of δ
2. Increase of τ
3. Increase of φ
4. Increase of ψ
5. Decrease of φ/τ
6. Increase of phase-displ. τ-φ
7. Decrease of φ/δ
8. Decrease of ψ'/φ

Fig. 13. Synthesis of the influence of the three factors to the significant parameters

A point that is worthy of more attention is the influence of the frequency to the parameter 6 (phase displacement τ-φ). Raising the frequency, we noted that the phase-displacement tended to a value α; we called it limit phase-displacement and found that it depends on the step p of the slalom. We deepened the matter making some new test in which we varied slalom step (performing at the maximum frequency), and found that the limit phase-displacement α is about 140° for steps larger than 8m, but is greater with shorter steps, as one can see in Fig. 13.

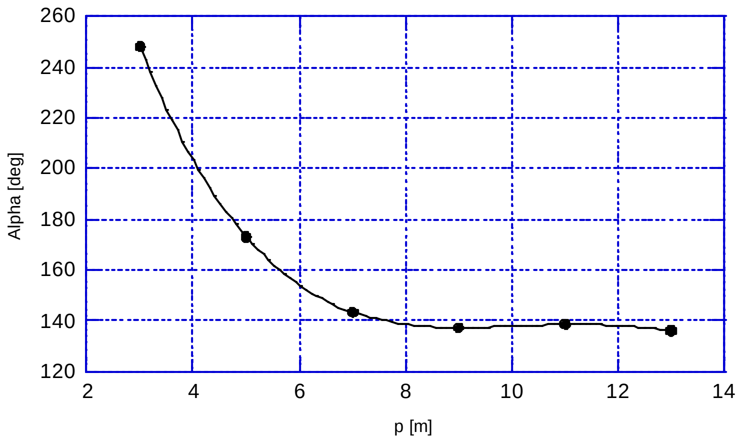

Fig. 13 Limit phase-displacement a in function of slalom step p

Observations and comparison with testers' impressions:

- An increase of slalom execution frequency changes the way of driving the scooter. In the same path, we have to steer less (lower δ) but with more force (higher τ) and we have to roll more (higher φ). As regards to calculated parameters, increasing the frequency, steering efficiency increases, but roll efficiency and specific roll decrease.
- The lowering of the roll centre that we obtain by passing from configuration III to configuration I, clearly influences four of the eight significant parameters. Using the configuration with lower roll centre (I) the driver has

to apply greater steering angles (in the same path and at the same frequency) and greater yaw angles; moreover, the specific roll (φ/τ) is lower and the pilot has to anticipate less the steering torque (the phase-displacement φ-τ is smaller). Both testers feel the scooter in configuration III handier than in configuration I but less stable.

- The increase of tyre diameter gives an increase of all measured parameters (from 1 to 4): in the same path, we have to steer more and with more force, we have to roll more and yaw more. This is compensated by a decrease of specific roll, steer efficiency and roll efficiency. Moreover, we have to apply steering torque τ with greater advance in respect to roll angle φ. All this changes point out that using the large front-tyre the scooter becomes less handy, as confirmed by testers' impressions.

By measuring the eight significant parameters, and by the confirmation given by driver's impressions, we can say that lowering the roll centre, passing from conf. III to conf. I and increasing of front-tyre diameter passing from tyre B to tyre A, the handling of this vehicle decreases. In the next paragraph, introducing a new index of handling we can valuate *how much* the handling varies changing the configuration of the quadrilateral and the front tyre model. In this way we can quantify the subjective test driver's impressions.

7. NEW HANDLING INDEX

We define limit frequency ν_{lim} the maximum frequency at which test driver can perform slalom of a certain step and with a certain vehicle. In order to highlight how limit frequency ν_{lim} varies changing the slalom step, we carry out a set of tests at maximum speed with cone spacing equal to 3, 5, 7, 9, 11 and 13 meters. We didn't test the three-wheeled vehicle for larger spacing than 13 meters because we reached the maximum speed using 13 meters. Using larger spacing doesn't make sense because increasing the step the limit frequency would decreases only because the speed can increase and not because of the dynamic limits of the vehicle and psychological of the driver.
The figure below shows the results obtained using the tire A and two extreme configurations I and III.

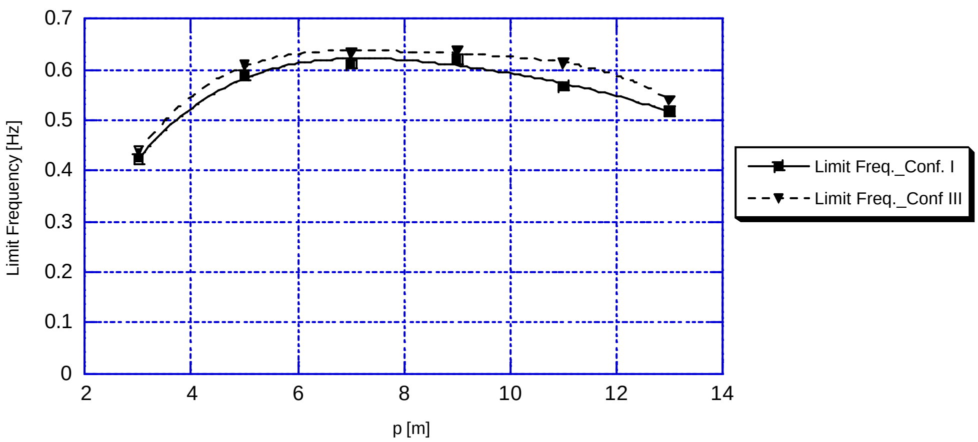

Fig. 14 Limit frequency in function of slalom step

You can observe that ν_{lim} is lower for small and large cone spacing. The scooter obstruction restricts ν_{lim} for small spacing, while both inertial and gyroscopic effects (which are more influential at high speed) restrict ν_{lim} for large spacing. The maximum is reached for medium spacing, in this case the maximum frequency about 0.65 Hz for cone spacing from 6 to 10 meters.
You can note that using the configuration III of the articulated quadrilateral the tester reach a higher ν_{lim} for every different spacing than using configuration I.

ν_{MAX} (conf I)= ν_{lim} (Conf . I, p = 7m)= 0.614 Hz
ν_{MAX} (conf III)= ν_{lim} (Conf III, p = 7m)= 0.650 Hz

If we calculate the ratio between the two values,

$$\frac{n_{\max}(conf\ \ III)}{n_{\max}(conf\ \ I)} = 1.058$$

We can say that the vehicle in the configuration III is 5.8% handier than in the configuration I.
We made the same tests adopting the intermediate configuration and using the tire A and B and we obtained:

$$\frac{n_{max}(tireB)}{n_{max}(tireA)} = 1.080$$

so we can say that the vehicle with the front tyre B is 8% handier than with the front tyre A.

Recapitulating, using the new index we reach two goals:

1. We demonstrate that the scooter is handier using the configuration III instead of I one and using the front tyre B instead of tyre A. This fact is in concordance with the information taken from the measurement of the eight significant parameters and with the driver's impressions.
2. We obtain a quantitative piece of information about the variation of handling owing to different geometrical characteristic of the vehicle. For example now we can say that the configuration (handy increase of 5.8% using conf. III instead conf. I) is less important than front tire (handy increase of 8% using tyre B instead of tyre A).

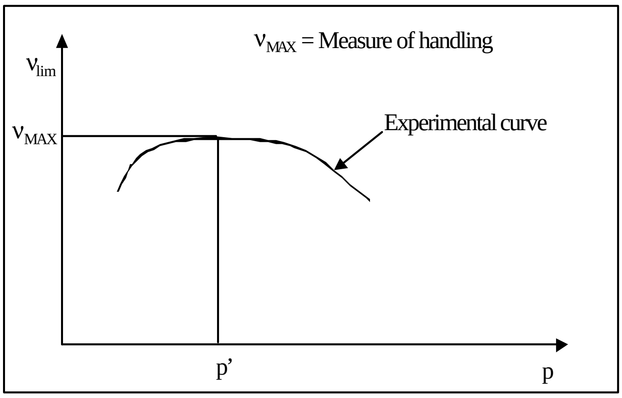

Fig. 15 Definition of a new index to measure the handling of a motocycle

In this study we propose as a new index for measuring the handling of a motorcycle the ν_{MAX}, defined as the maximum frequency at which a test driver with a certain motorcycle can perform a slalom path with straight-line equidistant cones. To obtain this measure it is necessary to build up experimentally a graph like the one in Fig. 14. This means to perform slalom paths of various steps and measure for each step the maximum frequency ν_{lim}, that is reached leading the vehicle to the limit of its performance. To make sure that the ν_{lim} reached is actually the highest possible, it is advisable to use many expert testers. The ν_{MAX} frequency (greatest among the ν_{lim}), obtained at the step p' of the slalom, is a measure of the handling of the motorcycle (Fig. 15).

8. CONCLUSIONS

In paragraph 6 we measured the variations of handling consequent to some changes in the set-up of the three-wheeled vehicle. The new index is in accord with the significant parameters calculated and with the test driver's impressions. So we can say that ν_{MAX} is a good index for handling.
Moreover, it is not fundamental to perform the test with a great number of different steps p to find out the step p', which correspond to ν_{MAX}. In fact ν_{lim} doesn't change very much in a quite interval of p, so it is sufficient to carry out the test for a restrict field of step depending upon the kind of motorcycle.
In conclusion, the new test for handling is proposed:

- to better describe the properties of a certain vehicle, with a new objective data item (ν_{MAX}) like maximum speed, maximum power and maximum torque.
- to have a measure of how much the handling increases or decreases consequently to a certain change of set-up in a motorcycle.

BIBLIOGRAPHY

1. F. Biral : *La Manovra Ottima per l'analisi delle prestazioni dei motocicli*, Mototecnica, May 2000.
2. D. Danesin: *Prototipazione virtuale di un veicolo innovativo rollante a tre ruote con un codice multi-body*, Graduations Thesis, University of Padua, 1999.
3. R. Berritta, F. Biral, V. Cossalter, N. Ruffo: *Development of a Novel Three Wheeled Vehicle*, 3. International Motorcycle Conference, Munchen, Germany, September 2000.
4. N. Ruffo: *Progettazione e Realizzazione di un Veicolo Innovativo Rollante a Tre Ruote*, Graduations Thesis, University of Padua, March 1999.
5. F. Biral, D. Bortoluzzi, V. Cossalter, M. Da Lio: *Experimental Study of Motorcycle Transfer Functions for Evaluating Handling*, Vehicle System Dynamics Vol. 39, No. 1, 2003
6. D. Bortoluzzi: *Studi Sperimentali e Teorici sulla Manovrabilità, Maneggevolezza e Stabilità di Veicoli a Due Ruote per il Miglioramento della Sicurezza*, Ph.D. Thesis, University of Brescia, 2001.
7. V. Cossalter: *Cinematica e Dinamica della Motocicletta*, Edizioni Progetto, Padova, 2001.
8. V. Cossalter: *Motorcycle Dynamics*, Race Dynamics Motorsports Engineering, Franklin (Wisconsin),USA, 2002.