Delft University of Technology, Yamaha Motor Europe NV

Rider Analysis

using a fully instrumented motorcycle

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using a fully instrumented motorcycle

Master of Science Thesis

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The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled "**Rider Analysis, using a fully instrumented motorcycle**" by **Marc Vincent Christian Evertse** in partial fulfilment of the requirements for the degree of **Master of Science**.

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ABSTRACT

During this investigation, an accurate description has been made of how a rider is operating a motorcycle while performing a cornering manoeuvre and an avoidance manoeuvre. To obtain this description, a motorcycle has been fully instrumented with sensors which measure the rider input and the motorcycle response.

It will be demonstrated that manoeuvring a motorcycle is done by applying a steering torque. The idea that a rider is steering by using his body (which is a general accepted idea in the motorcycle industry, not necessarily in scientific research) appears to be incorrect, based on the results obtained in this project. The location or motion of the upper body does influence the required steering torque, but does not cause a significant response of the motorcycle. When the mental workload rises as a result of an increased velocity or in rainy conditions, riders have the tendency to use the upper body more.

Three categories of riders have participated in a test, policemen, test riders and beginners. The test consisted of a cornering manoeuvre and an avoidance manoeuvre. It will be demonstrated that all riders apply the same required steering input. Additionally they give an input directly in roll direction by using the upper body and that characteristic shows the main differences between the riders.

Beginners in particular apply a lot of force directly in roll direction, which makes them highly inefficient. Test riders efficiently make use of their upper body by 'hanging' into the corner. Policemen are doing the opposite by maintaining in upright position. This makes them less efficient but provides them more control.

During the tests, the beginners commented that the mental workload is the main factor that limits their performance. This aspect can be an explanation for their increased use of the upper body. There is no stereotype beginner. Overall their performance is lower, but within the category there is a large diversity.

By offering accurate insight on how different riders are operating a motorcycle, this can be used for educational purposes to increase the safety, efficiency and comfort of riding a motorcycle.

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Nomenclature

EI_ψ	Efficiency Index	$\frac{N}{rad/s^2}$
F_f	Lateral force front wheel	N
g	Gravity acceleration	m/s^2
I_{CXZ_f}	Moment of inertia front section in X-direction	kgm^2
I_{CYZ_f}	Moment of inertia front section in Y-direction	kgm^2
I_{W_f}	Moment of inertia front wheel	kgm^2
KI_φ	Koch Index	$\frac{N}{rad/s^2}$
LC_φ	Lane Change Index	$\frac{N}{rad/s^2}$
LC_ψ	New Lane Change Index	$\frac{N}{rad/s^2}$
M_{G_δ}	Gyroscopic moment generated by steering motion	Nm
M_{G_φ}	Gyroscopic moment generated by roll motion	Nm
M_{Y_f}	Twisting torque in Y-direction, front tire	Nm
M_{Z_f}	Twisting torque in Z-direction, front tire	Nm
N_f	Normal force front wheel	N
S_f	Longitudinal force front wheel	N
V	Velocity	m/s
X_{G_f}	X-location center of mass front section	m
X_{P_f}	X-location front wheel contact point	m
X_Q	X-location origin Q	m
Y_{G_f}	Y-location center of mass front section	m
Y_{P_f}	Y-location front wheel contact point	m
Y_Q	Y-location origin Q	m
Z_Q	Z-location origin Q	m

δ	Steering deflection	rad
$\dot{\delta}$	Steering rate	rad/s
Δ	Projection of steering deflection on ground plane	rad
ε	Caster angle	rad
μ	Pitch angle	rad
τ_δ	Applied steering torque (in steering direction)	Nm
$\dot{\tau}_\delta$	Steering torque rate	Nm/s
$\tau_{\delta\varphi}$	Total applied steering torque	Nm
φ	Roll angle	rad
$\dot{\varphi}$	Roll rate	rad/s
ψ	Yaw angle	rad

$\dot{\psi}$	Yaw rate	rad/s
ω_f	Spinning velocity front wheel	rad/s

1 Introduction

As in each discipline, safety is a big issue. Usually the government plays a role in this by making rules and regulations. On the contrary with the automobile branch, the motorcycle branch is relatively spared by these rules. Without interference of the governmental institutes, motorcycle manufacturers are actively trying to increase the safety of the motorcycle rider.

Many motorcycle manufactures renew some models of their fleet every two years. To increase safety and comfort during riding, the upgraded models are supposed to have an increased manoeuvrability and handling performance.
Manoeuvrability and handling describe the motorcycle's ability to execute complicated manoeuvres and the facility of which the rider is able to perform them, both physically and psychologically [2]. So instead of considering the motorcycle, it is interesting to take the rider as starting point for an investigation.
In literature, a lot is known about the motorcycle dynamics. Models and simulations make it possible to predict the response of the motorcycle on a variety of possible rider input, but what exactly is the rider input?
The questions that are the motivation for this investigation are:

How is a rider operating a motorcycle? Are there any differences between the riders? How does the rider experience the workload when performing a manoeuvre?

To find an answer to these questions, Yamaha has started an investigation to gain more insight in the way riders are operating a motorcycle. Not only the rider actions and motorcycle response will be analyzed, but also the rider himself will be involved.

The possible outcome of this project can be used by Yamaha for educational purposes. To increase safety and comfort during riding a motorcycle, they could give advanced rider training, specially addressed to a target group. Also in planning new models, they could decide to design a model specially for, for instance, beginners. If a link can be made between the data and the rider feeling, the results might be useful for racing activities, but that is not one of the targets.

In the next chapter the project plan is discussed. Chapter 3 contains the theory on motorcycle dynamics and the theory behind an existing evaluation method to rate performance and workload. To obtain data, a motorcycle will be provided with sensors and that is the subject of chapter 4. The preparation of the test is discussed in chapter 5. Chapter 6 and 7 contain the results. A discussion of the results and the conclusions can be found in chapters 8 and 9.

2 Project Plan

In order to investigate the way a rider is operating a motorcycle and how the rider is experiencing the workload, basically two things are needed: A motorcycle that is able to obtain data and an evaluation method. Following on that, a test has to be facilitated.

A motorcycle will be fully provided with sensors and the corresponding software to be able to retrieve and analyze the data. Before starting the preparation of this motorcycle, research will be done on motorcycle dynamics. It is evident that the knowledge on motorcycle dynamics is also required for a decent analysis of the data.
Apart from in-house evaluation methods of motorcycle manufacturers there is no existing evaluation method for motorcycle riding behaviour (according to the knowledge of the author). To obtain an evaluation method, an existing method in aviation will be investigated. This is the Cooper-Harper method [2] and this method is commonly used by pilots to rate the performance of an aircraft.
The theory behind both these subjects is explained in chapter 3.

Preparing the motorcycle, it is important that all the rider input can be measured as well as the motorcycle response. After placing the sensors, they need to be programmed and calibrated.

Once the motorcycle is fully equipped, it is time to collect data. To obtain a global view on rider operations and on the performance of the sensors, a variety of riders will ride the motorcycle under different circumstances and on different tracks. This is done in Italy. The weather is better and the country provides a large variety of roads with less traffic with respect to The Netherlands. Apart from this scheduled test, during the entire project data will be collected to gain more insight and to improve the test motorcycle. Preparation of the sensor equipment will be explained in chapter 4.

When it becomes clear how the riders operate the motorcycle and what the fields of interest are, one can prepare a large test. This test should contain interesting manoeuvres and should provide the possibility for riders to evaluate their performance. This starts with finding a suitable location. Then the group of riders has to be composed. The test set-up will be described in chapter 5.

Once the test has been carried out, the detailed analysis of the data can start. This will be the subject in chapter 6.

3 THEORY

This thesis concerns the analysis and comparison of different motorcycle riders. The analysis is done using the recorded data during the tests. The data is also used to compare the different riders in their handling efficiency. Both subjects require knowledge concerning motorcycle dynamics, and this will be the subject of the first part of the theory.

Another aspect of the tests is the self-evaluation of the riders. In aviation, it is common use for pilots to evaluate handling characteristics of aircraft. This evaluation is sometimes done according to a certain method, the Cooper Harper method [2]. This method will be elaborated in the second part of the theory.

3.1 MOTORCYCLE DYNAMICS

3.1.1 STEADY TURN

This first section refers to *steady turning*, to a motorcycle at a constant velocity and turn radius. In a turn with variable velocity and curvature radius, the torque that the rider must exercise will be substantially different from that calculated in a steady state, especially if the variations in velocity and trajectory occur suddenly. Non-steady turning is more realistic but for a clear understanding of the influence of various parameters, a steady state approach is more suitable.

3.1.1.1 MOMENT AROUND STEERING AXIS

The equilibrium of moments around the steering axis enables the evaluation of the torque τ that the rider must apply to the handlebars to assure the motorcycle's equilibrium in a turn.

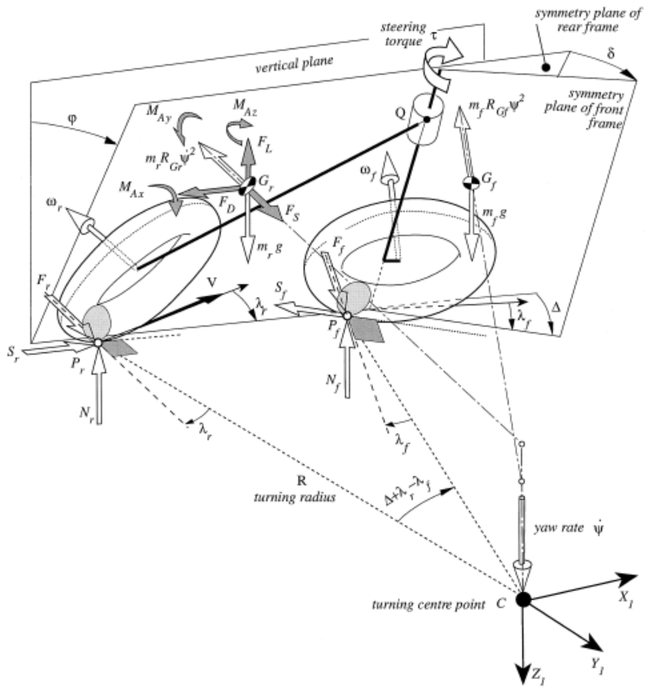

FIGURE 3.1: MOTORCYCLE IN STEADY TURNING [5]

In Figure 3.1, the coordinate system f(x, y, z) is fixed to the front frame and may be described as follows: its origin is located in point Q, which is the point of intersection between the steering axis and the plane perpendicular to the steering axis which passes through the centre of the rear wheel; axis z is aligned with the steering axis and points downwards; axis y is parallel to the rotation axis of the front wheel; axis x lies in the symmetry plane of the front frame.

The torque applied by the rider is equal, but of opposite sign, to the resultant of all the moments generated by the forces acting on the front section. The resultant torque is composed of 7 terms, derived from the figure and discussed here in order of magnitude [5]:

$$\tau = \tau_F + \tau_N + \tau_M + \tau_G + \tau_\psi + \tau_\omega + \tau_S \tag{3.1}$$

- Where the first term is the aligning influence due to the lateral force on the front wheel:
  $$\tau_F = [(Y_Q - Y_{P_f})sin\Delta + (X_Q - X_{P_f})cos\Delta]cos(\mu+\varepsilon)cos\varphi F_f - Z_Q[cos\Delta sin(\mu+\varepsilon) - cos(\mu+\varepsilon)sin\varphi sin\Delta]F_f \tag{3.2}$$

In which μ and ε represent respectively the angle of pitch and the caster angle. Other parameters can be found in the figure.

- The second term is the disaligning influence due to the normal load on the front wheel:
  $$\tau_N = [(Y_Q - Y_{P_f})sin(\mu+\varepsilon) + (X_Q - X_{P_f})cos(\mu+\varepsilon)sin\varphi]N_f \tag{3.3}$$
- The third term is the disaligning effect of the twisting torque of the front tire:
  $$\tau_M = -M_{Z_f}cos(\mu+\varepsilon)cos\varphi + [cos(\mu+\varepsilon)sin\varphi cos\Delta + sin(\mu+\varepsilon)sin\Delta]M_{Y_f} \tag{3.4}$$
- The fourth term is the disaligning influence due to the effect of gravity:
  $$\tau_G = gm_f[(Y_Q - Y_{G_f})sin(\mu+\varepsilon) + (X_Q - X_{G_f})cos(\mu+\varepsilon)sin\varphi] \tag{3.5}$$
- The fifth term is the aligning effect due to centrifugal force of the front section:
  $$\tau_\psi = \dot\psi^2 m_f(Y_{G_f}X_Q - X_{G_f}Y_Q)cos(\mu+\varepsilon)cos\varphi - \dot\psi^2 m_f Z_Q(Y_{G_f}sin(\mu+\varepsilon) + X_{G_f}cos(\mu+\varepsilon)sin\varphi) + \dot\psi^2[I_{CYZ_f}sin(\mu+\varepsilon) + I_{CXZ_f}cos(\mu+\varepsilon)sin\varphi] \tag{3.6}$$
- The sixth term will be the aligning influence of the gyroscopic effect of the front wheel:
  $$\tau_\omega = [sin\delta sin\varphi - cos\delta cos\varphi sin(\mu+\varepsilon)]I_{W_f}\omega_f\dot\psi \tag{3.7}$$
- The last term is the disaligning influence due to the longitudinal force on the front wheel:
  $$\tau_S = [(Y_{P_f} - Y_Q)cos\Delta + (X_Q - X_{P_f})sin\Delta]cos(\mu+\varepsilon)cos\varphi S_f - Z_Q[cos\Delta cos(\mu+\varepsilon)sin\varphi + sin\Delta sin(\mu+\varepsilon)]S_f \tag{3.8}$$

The steering torque exerted by the rider may also be calculated with the equilibrium equations of the rear frame.

Making a summary of what has been shown here, the various components have the following effect:

- The vertical load: the vertical reaction force generates a positive moment of high value.
- The lateral reactive force generates a high value negative moment of about the same order of magnitude as the vertical load.
- The front weight force generates a positive moment
- The centrifugal force generates a negative moment of about the same order of magnitude as the weight force.
- The gyroscopic moment generates an aligning effect.
- The twisting moment generates a disaligning effect that increases with the roll angle.

The torque is positive when it tends to increase the steering angle and negative if it tends to align the front section. In Figure 3.2, a common variation of the torque (Nm) applied by the rider to the handlebars is shown as a function of the speed and curvature.

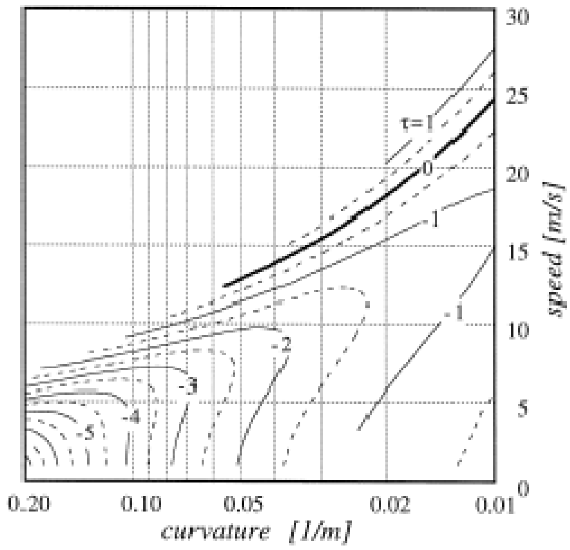

FIGURE 3.2: STEERING TORQUE AGAINST CURVATURE AND VELOCITY [4]

There are two basic characteristics that can be derived from this figure:

- At low velocities the steering torque is negative. This phenomenon is further enhanced at small corner radii. It means that the rider has to block the handlebars from rotating further. A highly negative applied torque indicates that the motorcycle is likely to turn very rapidly, which can be favourable under certain circumstances like in racing.
- As the velocity increases, the torque becomes positive. When this becomes too large, the rider has the unpleasant experience of riding a motorcycle which is difficult to turn.

The maximum manoeuvrability is obtained when the moment necessary for assuring equilibrium is zero or nearly so. Under these conditions, if the rider lets go of the handlebars the motorcycle continues to round the turn set.

3.1.1.2 Influence of motorcycle geometry and rider displacement on the steering torque

The influence of the motorcycle geometry can be derived from the equations of motion. The most important geometric parameters are discussed below and defined in Figure 3.3. The influence of the other geometrical parameters are listed later on in Figure 3.5.

- Normal trail: The normal trail has a disaligning effect. This is due to the fact that the disaligning effect of the front tire vertical load increases more than the aligning effect of the lateral force.
- Caster angle: On the contrary, the increase in caster angle has an aligning effect. This is due to the fact that the moment caused by the lateral force increases.
- Front tire cross section radius: An increment in front tire head radius has a strong aligning influence. First of all this is caused by the displacement of the front wheel contact patch due to the roll angle. The second reason for this is that the motorcycle tends to pitch backwards, which increases the caster angle again.

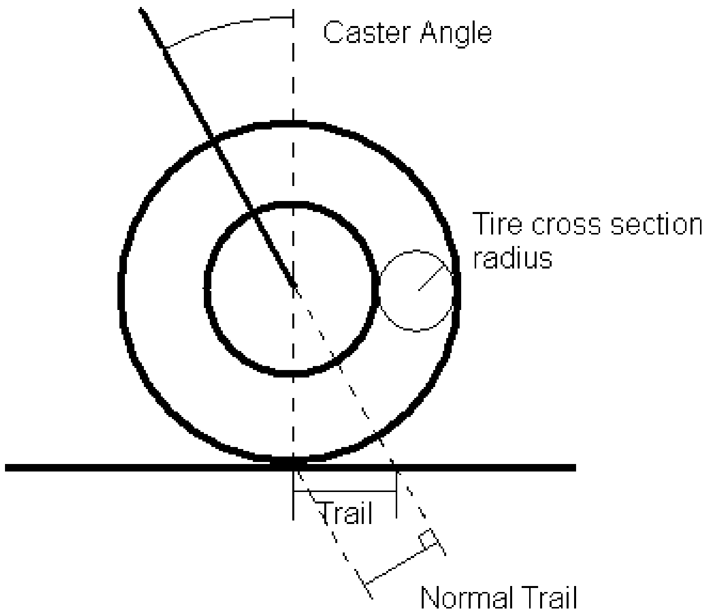

FIGURE 3.3: DEFINITION OF MOST IMPORTANT GEOMETRIC PARAMETERS

A forward displacement of the rider's center of mass has a slight self-steering effect. The vertical position of the rider's center of mass has a small aligning effect in case of an increasing height. The result is that if the rider's center of mass remains in the plane of symmetry of the motorcycle, the steering behaviour doesn't change significantly. On the contrary, a rider lateral displacement inside the curve, causing a moment input in roll direction, has a strong aligning effect. Considering that sports riders usually move laterally a lot, the steering characteristics of the motorcycle are strongly modified by the riding style. An expert rider can take advantage of this possibility to shift his weight in such a manner that it results in a steering behaviour that requires less force. Also the lateral motion itself causes a moment in roll direction which has a similar effect.

The influence of the rider's lateral position on the steering behaviour of the motorcycle is represented in Figure 3.4, which is the result of a multi-body model. A 0.05 m lateral displacement of the rider's center of mass inside the curve is considered, which results (in this case) in a decrease in roll angle of about 1°. The figure shows the steering ratio (ratio between steering torque and the lateral acceleration, steady state) both in the presence of lateral displacement and under normal conditions, for different velocities and corner radii.

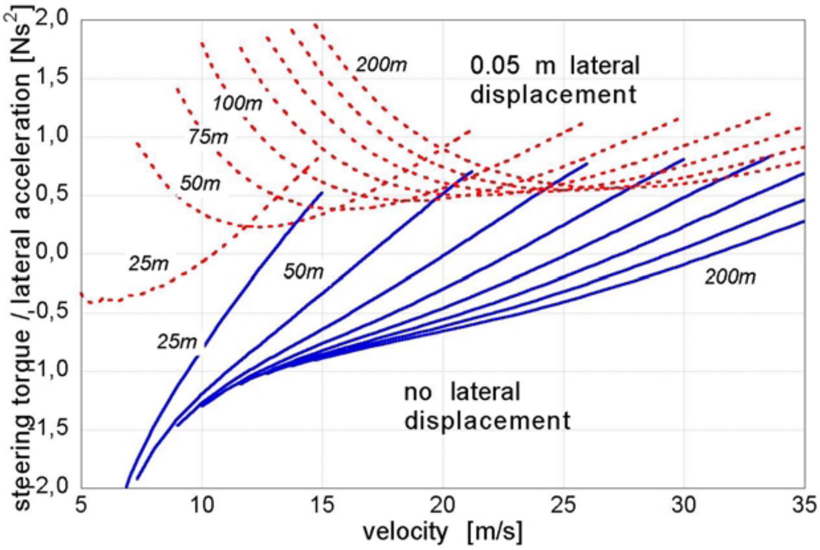

FIGURE 3.4: INFLUENCE OF RIDER'S LATERAL DISPLACEMENT ON THE STEERING TORQUE [4]

It is clearly visible that the difference between the two curves becomes very large when the velocity and corner radius are low. This behaviour can be explained by taking into account the effect due to the decrease in roll angle caused by the rider's lateral displacement. The first effect is the decrease of the disaligning effect of the tire twisting torque. The second effect is the variation of the moment of tire forces around the steering axis. In particular the disaligning effect of the tire vertical load, which tends to rotate the wheel towards the inside of the curve, decreases.

We have seen that many modifications to the motorcycle will bring variations in the torque applied to the handlebars. The influence of the main geometrical and inertial parameters, as well as the influence of the lateral displacement of the rider are shown in Figure 3.5.

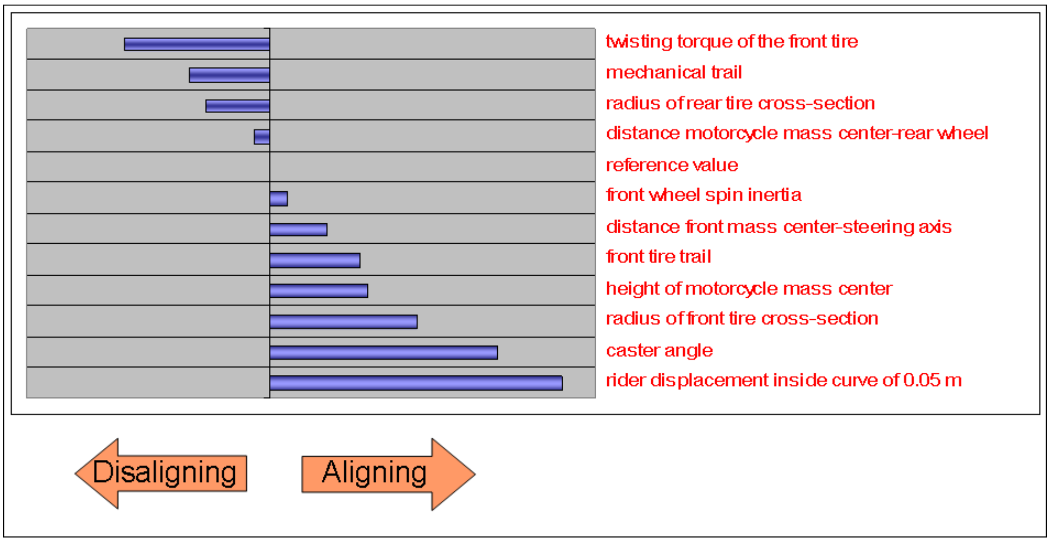

FIGURE 3.5: INFLUENCE OF MAJOR PARAMETERS ON STEERING TORQUE [4]

All parameters have been increased with 10 percent relative to their base value and their influence is compared with an inward rider displacement of 0.05 m.

3.1.2 UNSTEADY TURNING (ENTERING AND EXITING)

When entering a corner, a rider can decide to use his upper or lower body to initiate the roll motion. The resulting force originating from that can act on the tank, on the seat, on the footrests or vertically on the handlebar. These body forces are usually omitted in the equations of motion. However, the work that is applied and the effect of it can be significantly. For this reason, these parameters will be taken into account during this investigation.

Not only can the rider decide about transferring his weight, he also has other possibilities to control his turn. The rider can use the brakes to help him entering a curve. The braking phase causes a pitch forward motion. This results in a smaller caster angle, which in turn results in a decreasing effect of the aligning lateral force moment. The opposite is also true; opening the throttle while exiting the curve results in a pitch backward motion which helps exiting the corner.

While entering and exiting corners, other gyroscopic effects than described in the previous section play an important role. In steady turning the gyroscopic effect is generated by the yaw motion, but in the non-steady case there are two extra gyroscopic effects; one generated by the roll-motion and one generated by the steering motion. There are also some effects due to the rotation of the crankshaft in the engine, but that is outside the scope of this project.

3.1.2.1 GYROSCOPIC EFFECTS GENERATED BY ROLL MOTION

We will concentrate on the front wheel while the motorcycle is rolling to the right. The front-wheel spin, coupled with the roll to the right, generates a gyroscopic moment M_g that acts on the front frame around an axis lying in the plane of the motorcycle perpendicular to the longitudinal roll axis:

$$M_{G_\varphi} = -I_{w_f}\omega_f\dot{\varphi} \tag{3.9}$$

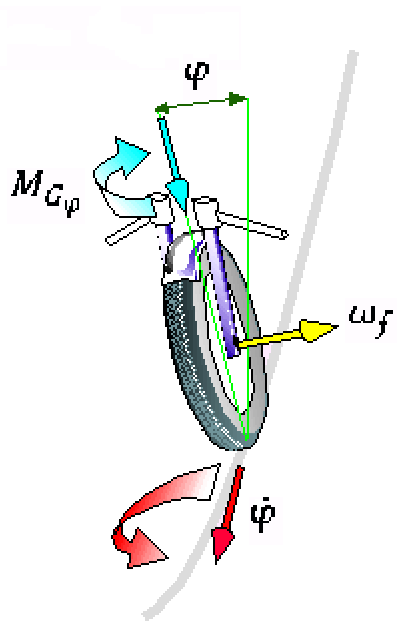

FIGURE 3.6: GYROSCOPIC EFFECT GENERATED BY ROLL MOTION [4]

The projection along the steering axis provides the beneficial moment around the steering axis:

$$M_{G_\varphi} = -I_{w_f}\omega_f\dot{\varphi}cos\varepsilon \tag{3.10}$$

Thus, as shown in Figure 3.6, the gyroscopic moment has the effect of turning the steering head to the right, thereby 'helping' the motorcycle enter the turn. Analogously, when the roll changes sign and the motorcycle returns to the vertical position, the gyroscopic moment has the effect of reducing the steering angle, thereby 'helping' the motorcycle exit the turn and return to rectilinear motion. The above mentioned influences are the same in both directions. The caster angle is of major influence and has to be chosen in such a way that it actually 'helps' in the functionality of the motorcycle. So, in each motorcycle segment one has to find a proper setting for the caster angle in order to fine-tune the actual 'help' that the gyroscopic effect is providing.

3.1.2.2 GYROSCOPIC EFFECTS GENERATED BY STEERING MOTION

Since the wheel's direction of spin is perpendicular to the steering head axis, turning the handlebars from right to left generates a gyroscopic moment around an axis perpendicular to both the steering head axis as well as the axis of the front wheel:

$$M_{G_\delta} = I_{w_f}\omega_f\dot{\delta} \tag{3.11}$$

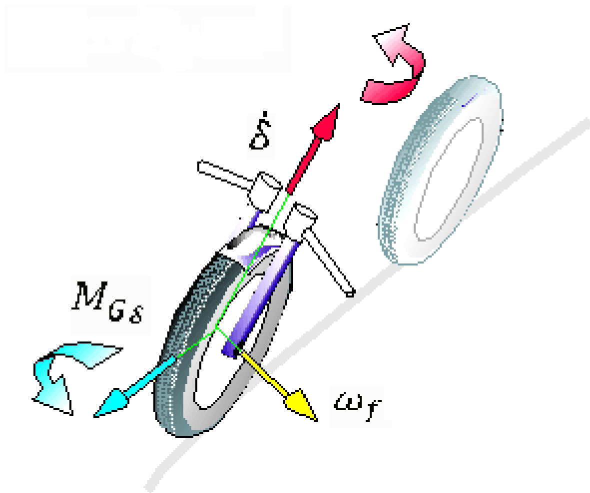

Figure 3.7: Gyroscopic effect generated by steering motion [4]

This has the effect of leaning the motorcycle over towards the right, Figure 3.7. Again, this phenomenon is the same in both directions. The projection of the gyroscopic moment on the roll axis is as follows:

$$M_{G_\delta} = I_{w_f} \omega_f \dot{\delta} cos\varepsilon \tag{3.12}$$

Considering this gyroscopic effect, one might conclude that this is an unfavourable destabilizing effect. In one way that's true, if you consider straight motion. But since a rider is always counter steering in a corner it turns out to be a beneficial effect. In applying force on the handlebar, the rider doesn't have to 'switch sign' while entering the corner. Once the motorcycle is rolling, the handlebar will follow the direction according to the previous described gyroscopic effect caused by the *roll* motion.

3.1.3 Handling Efficiency

During this investigation, different riders will be compared performing different manoeuvres. Not only the characteristics of the handling operations are concerned, but also the efficiency of how they operate the motorcycle. This will be done according to an already existing relationship, the Koch Index.

3.1.3.1 Koch Index

To quantify the characteristics of the motorcycle's handling qualities, J. Koch [3] proposed the following index after experimental tests in "U" turns:

$$Koch\ Index = \frac{\tau_{\delta peak}}{V \cdot \dot{\varphi}_{peak}} \left[\frac{N}{rad/s^2}\right] \tag{3.13}$$

This equations relates the riders steering torque peak as the input with the roll velocity as the desired output, normalized by the velocity. This index is used to demonstrate the capacity of a motorcycle to enter a turn. The main purpose of the Koch index is to compare the handling qualities of different types of motorcycles.

During this investigation, the purpose is to compare different riders with their corresponding riding style. Instead of relating the rider input with the roll velocity that mainly describes the agility of the motorcycle, it would be more interesting to have a relation containing a parameter that indicates how fast a rider is actually turning. This is represented by the yaw velocity or yaw rate, $\dot{\psi}$.
Also on the input side, just the steering torque is not covering the input entirely. A better option would be to include the total moment applied on the steering bar, so the resultant moment of both components in steering direction and in roll direction. This will result in the total input moment on the steering bar, $\tau_{\delta\varphi}$. This will end up in the following expression for the 'Efficiency Index':

$$Efficiency\ Index = \frac{\tau_{\delta\varphi\ peak}}{V \cdot \dot{\psi}_{peak}} \left[\frac{N}{rad/s^2}\right] \tag{3.14}$$

3.1.3.2 Lane Change Index

To quantify the efficiency of which the riders are operating the motorcycle during the lane change manoeuvre, Cossalter and Sadauckas introduced a modified version of the Koch Index, the Lane Change Roll Index [3]:

$$Lane\ Change\ Roll\ Index = \frac{\tau_{\delta\ peak-peak}}{V_{avg} \cdot \dot{\varphi}_{peak-peak}} \left[\frac{N}{rad/s^2}\right] \tag{3.15}$$

As the manoeuvre consists of a double steering motion in two directions, the common steering torque τ_δ is replaced by the peak-to-peak value $\tau_{\delta\ peak-peak}$. The same holds for the roll rate, $\dot{\varphi}_{peak-peak}$. Some riders may put the largest part of their effort in the first steering motion and less in the second, or vice versa. By taking the peak-to-peak value, that characteristic cannot play a role in the comparison and the complete manoeuvre is concerned.

One of the phenomena that requires the majority of the steering input is the gyroscopic effect originating from the roll velocity and the rotational velocity of the front wheel. As this effect is linearly depending on the velocity, this parameter is included in the numerator of the index. Usually a lane change manoeuvre is performed with a constant velocity, nevertheless the average will be taken over the complete trajectory.

In compliance with the earlier objections against the Koch index, this index is modified to fit the purpose of the test, comparing riders. This gives the following equation:

$$New\ Lane\ Change\ Roll\ Index = \frac{\tau_{\delta\varphi\ peak-peak}}{V_{avg} \cdot \dot{\psi}_{peak-peak}} \left[\frac{N}{rad/s^2}\right] \tag{3.16}$$

During this investigation, all four indices will be used and mutually compared.

3.2 Evaluation Method

A purpose of this thesis is to relate the experiences and perceived effort of the riders with the collected data. To capture these experiences a method will be used that is commonly used in aviation by pilots to rate and evaluate the handling qualities of an aircraft. This rating is done according to a Cooper-Harper Rating Scale. Using this method, the pilot actually rates his own performance and he can describe his difficulties in whatever he is attempting. In this section the theoretical background of the method will be discussed. The adaptation and application of this method in this investigation will be elaborated in chapter 5 concerning the test set-up.

3.2.1 Handling Quality Criteria

“Handling qualities” is defined as “those qualities or characteristics of a vehicle that govern the ease and precision with which the pilot is able to perform certain tasks.” Handling qualities are more than just stability and control characteristics of the vehicle. Other characteristics that influence the handling qualities are the cockpit interface, the environment, mental and physical condition. [2]

The method to determine HQs is in the following order:

1. Theoretical analysis on dynamical motorcycle behaviour
2. Experimental performance measurement
    a. Pilot input
    b. Pilot-vehicle output
3. Pilot evaluation

At present, there are some mathematical representations of the human operator, but they are restricted to simple tasks. Although theoretical analysis is fundamental to the analytical prediction of HQs, it cannot adequately treat the complex interactions that are now investigated by means of experimental pilot evaluation.
Fundamental to any handling qualities program is a clear definition of the primary objective of the program. Therefore a clear description and understanding between the engineer and the test-pilot is required. This description must include: (a) what the pilot is required to accomplish with the vehicle, and (b) the conditions or circumstances under which the mission is to be conducted.

From normal operational use, when you cut the mission in parts, the Mission Task Elements (MTE) follow. [11] From these MTEs, the test manoeuvres can be determined. In defining performance standards for HQ manoeuvres, it is important to select constraints that will expose any handling deficiencies, but they still have to be realistic and reflect the real world.
In order to expose certain tendencies, constraints need to be tightened. This will give better results and may reveal certain cliffs. Limits on desired and adequate performance are an essential part of any manoeuvre description. They set the level of pilot gain and assist the pilot in his evaluation of the HQs.

A test manoeuvre has to meet the following set of requirements: [12]

1. Applicability to specific mission task elements
2. Ease of testing; build up aggressiveness
3. Task and constraint performance must be definable
4. Cover all levels of manoeuvre amplitude
5. Adaptability to other motorcycles
6. Has to produce useful data

3.2.2 Pilot Rating

Pilot evaluation data generally consists of: (1) the pilot rating, or shorthand representation of the operational characteristics, and (2) the pilot comments that identify those characteristics that interfere with the intended use.

A pilot rating is a portion of the technical report of the evaluator, and is the overall summation of the suitability of the vehicle for the specified use. The *pilot rating scale* is then a systematic means of denoting the quality of the pilot-vehicle combination in the accomplishment of its intended purpose. In his rating, the pilot can reach four 'kinds' of quality: [2]

1. Satisfactory – good enough without improvement
2. Tolerable – adequate for the purpose but improvements are desirable
3. Unacceptable – not suitable for the purpose, but still controllable
4. Uncontrollable

By considering the following three decisions, the pilot will arrive at one of the four categories previously mentioned:

1. Is the vehicle controllable?
2. Is adequate performance attainable with a tolerable workload?
3. Is the vehicle satisfactory without improvement?

The complete revised rating scale that originates from the questions above is shown in Figure 3.8.

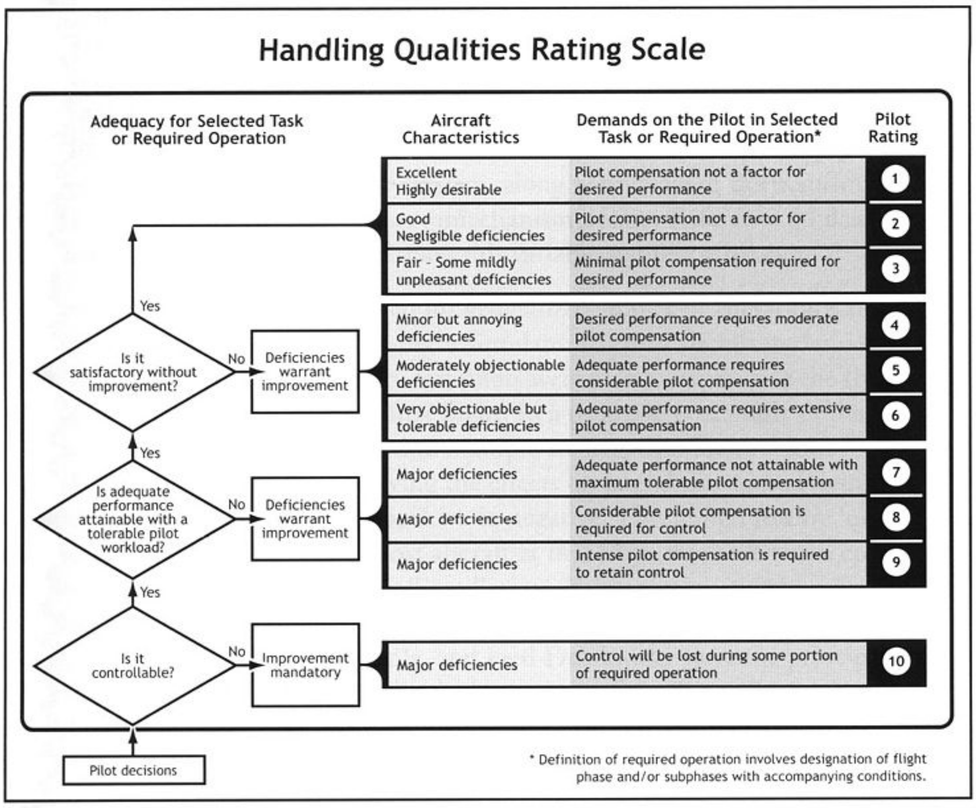

Figure 3.8: Cooper-Harper HQs rating scale [2]

The top three quality categories are further subdivided to add minor quality differences and to come to a final rating from zero to ten.

The rating is meaningless without comment. The pilot should report what he sees and feels, and describe his difficulties in carrying out whatever he is attempting. It is important then that the pilot relates his difficulties to the effect on the accomplishment of the required task. Therefore, ratings and comments should be given on the spot, when the characteristics are still fresh in mind. Questionnaires or explicit checklists ensure that all important or suspected aspects are considered and that the reason for a given rating is specified. It is even recommended that pilots participate in the preparations of the questionnaires.

Once the manoeuvre has been finished there are a few issues to keep in mind regarding the obtained data and the obtained rating: End game corrections during the manoeuvre might result in good performance, but are indicative for bad handling. There is also a possibility that a certain learning curve occurs, a pilot may perform better when he has completed the manoeuvre a couple of times. If there is a discrepancy between the perceived and the achieved performance, this can imply that the rating is unlikely to accurately represent the achieved performance. A possible cause for this can be unclear task cues.

4 Motorcycle Preparation

To measure the rider actions and the response of the rider/motorcycle combination, a motorcycle is equipped with sensors. The test motorcycle is a Yamaha FZ6 fazer, of which a data sheet is available in appendix 1. The motorcycle is fully instrumented with a 2D (Debus & Diebold) data-recording system. This system consists of hardware in the form of sensors, connectors and on-board data storage capacity (logger) completed with additional sensors of different brands. All the used equipment is of the shelf technology.
The other part of the system is the software to program and calibrate the logger and the sensors and to analyze the data. This software is also provided by 2D.
A description of the instrumented bike will be given in subsequent sections. More extensive sensor information can be found in the corresponding spec sheets in appendix 2.

4.1 Hardware

There are two types of data to be measured; the rider input and the rider/motorcycle output. The rider input consists of forces and operations. The output consists of the heading, attitude and accelerations.

4.1.1 Input Sensing

There are various contact points between rider and motorcycle at which the rider can either apply or experience a force. Those contact points are: the handlebar, the seat, the footrests and the tank. They are discussed below with the corresponding sensor. The sensors and their location are shown in Figure 4.1.

Figure 4.1: Input sensing

1. *Handlebar*

   On both sides of the handlebar a BI-AXIAL LOAD ARM is mounted. This load arm measures the applied steering force in two directions; one perpendicular to the front fork and perpendicular to the grip and one in the direction of the front fork and perpendicular to the grip. The first one senses the actual force in steering direction. The second one measures the force perpendicular to the steering direction in the direction of the font fork. The exact location at which the forces are measured is 300 millimeter away from the symmetry plane of the motorcycle.
2. *Seat*

   Under the seat, four LOAD BUTTONS are mounted. Two are located in the front and two in the back, divided in left and right. All load cells measure the load in vertical direction. The load cells are located 86 and 103 millimeter away from the motorcycles plane of symmetry for respectively the front pair and the rear pair.
3. *Footrests*

   In both footrests a LOAD BUTTON is mounted. It measures the force on the footrests in vertical direction. The load cells are located 240 millimeter away from the motorcycles plane of symmetry.
4. *Tank*

   To measure the force acting on the tank by the riders leg or knee, a LOAD BUTTON is mounted on each site of the tank. It measures the force in lateral direction at 740 millimeter above the ground.

Apart from sensing forces, also the operations during braking and operating the throttle are measured. They are not taken into account in the calculations, but they might provide the necessary information to clarify certain characteristics visible in the data. They follow below.

1. *Braking Pressure*

   For both the front brake (lever on right side of the handlebar) as the rear brake (lever on right footrest) the braking pressure is measured. The PRESSURE SENSORS were mounted ahead of the tubes of the hydraulic system.
2. *Throttle position and engine RPM*

   The throttle position and engine RPM is measured by the CPU of the motorcycle already, so it was only necessary to shortcut the circuit to capture the signals.

To prevent false interpretation of the data, a SMALL CAMERA is mounted on the windshield to observe the rider. The complete upper body was visible, including the handlebar. The 30 Hz video images are directly linked with the data using the data analysis software, so this gives an accurate view of the rider. To make sure the images are synchronized with the data, a trigger is mounted. This trigger gives a signal in the data and at the exact same moment it blinks a small led, which is visible in the video.

4.1.2 Output Sensing

The output or response of the motorcycle is also measured. This globally consists of position and heading, velocity, acceleration, attitude and steering deflection. See Figure 4.2.

Figure 4.2: Output Sensing

1. *Position and Heading*

   To measure the heading and location of the motorcycle, a GPS SENSOR is used. The GPS measures the location and can be used to calculate the velocity and yaw angle of the motorcycle.

2. *Velocity*

   Apart from the GPS measurement, the velocity is also determined measuring the rotational velocity of both the front as the rear wheel. This is measured using an INDUCTIVE SPEED SENSOR, which reacts on crossing bolds of for example the brake disc. In turn, the velocity can be used to calculate the acceleration.

3. *Acceleration*

   To measure the acceleration, two ACCELEROMETERS are mounted just on top of the engine under the tank. One in longitudinal direction and one in lateral direction, fixed to the motorcycle.

4. *Attitude*

   Three rotations exist in the dynamics of the motorcycle, to be; pitch, roll and yaw. The first one, pitch, is calculated using the elongation of the springs of the front and rear suspension. The elongation is measured with a LINEAR POTENTIOMETER attached at both ends of the suspension.
   The roll angle is measured using two LASER DISTANCE SENSORS on both sides of the motorcycle which measure the riding height. Both sensors are located at a 130 millimeter distance from the motorcycle plane of symmetry. Initially, a gyro was used to determine the roll angle but within one lap the roll angle was already 10 degrees off. This was not to be solved easily, so a new way of measuring the roll angle had to be found.
   The yaw angle of the path of the contact point of the rear wheel is calculated using the GPS coordinates and the roll angle. This will not require any further instruments.

5. *Steering deflection*
   A rotational potentiometer measures de steering deflection.

The input and output is recorded and stored on board in two compact, low weight data loggers that are mutually connected. The camera is connected to its own on board data storage device and the images will be imported and synchronized later in the data analysis software.

4.2 Software

The software that has been used was from 2D (Debus & Diebold) Data Recording Systems. This software provides the programming and calibration of the sensors, the recording of the data (logging) and the analysis of the data.

4.2.1 Sensor Programming and Calibration

The sensors deliver an output voltage of 0-5 V. The logger has to be programmed in such a way that it converts this voltage in the correct values. To obtain the correct values, an offset and a multiplication factor are used. Temperature changes and current leakage influence the output voltage of the sensors. Therefore, all sensors are calibrated before each test.

4.2.2 Data Recording

The test data is recorded and stored by the logger. After the test, the logger will be connected with the PC to obtain the data. When the data is stored on the computer, the data analysis can start.

4.2.3 Data Analysis

In the analyzer, all the input and output channels can be visualized in a moving plot. At the same time, a plot of the track can be made using the GPS input. It is possible to scroll through the data and along the track synchronously. The analysis can be extended by linking the video images with the data. In that way it is possible to scroll through the data and directly see what the rider is doing at each part of the track.

On the input side, basically all interesting parameters are measured directly. They just need to be multiplied by an arm length to obtain moments instead of forces. This does not hold for the output side. Especially the rotations around the three axis require some calculations.

Pitch

The pitch angle is calculated by measuring the spring elongations on the front and rear side of the motorcycle. Combined with the wheelbase, the angle of pitch is calculated with the tangent function.

Roll

The roll angle is calculated in the same way as the pitch angle, using the difference of the measured riding height of the left and right side of the motorcycle combined with the distance between the sensors. The ride height is corrected with the pitch angle, before it is included in the calculation.

Yaw

The calculation of the yaw angle at the rear wheel is done using the GPS data. The GPS measures the location in degrees in North Latitude and West Longitude. This data is converted to an X and Y location in meters in a horizontal plane. The derivatives of both the X-location and Y-location give the velocity in X and Y direction. The tangent is used to calculate the yaw angle of the GPS sensor. As it is more interesting to know the yaw angle at the location of the contact point of the rear wheel with the tarmac, the height of the location of the sensor combined with the roll angle is used to calculate this. The location of the calculated contact point lies in the symmetry plane of the motorcycle and has not been corrected for the fact that it moves sideways due to the thickness of the tire.

The calculation tools provided by the analysis software are basic but sufficient. Simple adding/subtracting and multiplying/dividing calculations are included but also derivations, different sorts of loops and noise filtering of the raw data.

5 Test Set-Up

The main purpose of the test is to obtain data about how a rider is operating the motorcycle. Using the data, differences in handling characteristics, handling efficiency and handling performance are elaborated. A second point of interest is how riders experience riding a motorcycle. This means that the tests should consists of two things: the manoeuvres and a rider evaluation after the manoeuvres. Therefore, the test is prepared starting from the principles of the Cooper-Harper method for handling quality rating. This method is commonly used in aviation industry by pilots and is referred to in the theory chapter. The purpose is to apply the method in developing manoeuvres and an evaluation questionnaire.

Ten riders in total will perform the tests, divided over three main categories, policemen, test riders and beginners. The major part of the test contenders has not been involved in a test like this, and due to the diversity of the riders, the main challenge is to create a test suitable for all riders. Apart from the manoeuvre itself, all riders should be able to evaluate their own performance.

Referring to the theory and to what is written above the manoeuvres have to meet the following requirements:

1. It has to produce useful data. The analyst has to be able to identify certain handling characteristics and therefore the manoeuvre should not include too many elements that require control actions from the rider.
2. There has to be a possibility to vary the aggressiveness of the test, as the level of experience of the riders is very divers.
3. Performance criteria must be definable. In this way, a rider knows what is expected from him and consequently he knows what he has to evaluate.
4. The rider has to be able to monitor or assess his performance. Indicators of the performance should be easy to check (e.g. speed indicator).
5. Equal circumstances for all contenders. To make a fair comparison between the riders, all conditions should be the same (e.g. environmental or traffic)
6. The manoeuvres should be safe and within the capability of all contenders. All riders have to be comfortable and the risks should be minimal.

5.1 Location

As we are interested in the normal operating characteristics of the riders, the tests could be performed on normal public road. But as riders are compared mutually, the circumstances have to be the same for all riders. Unfortunately, this is not the case due to the daily traffic. To provide a place with equal circumstances that guarantees the safety for all the riders, the choice is made to perform the tests on a closed track.

With the courtesy of the Dutch Police Academy, the tests were performed on their closed training circuit in Lelystad (The Netherlands). The track provides a smooth clean surface and a variety of corners.

Despite of the excellent conditions provided by the track, there is one minor drawback: time. The track is heavily occupied which resulted in one-and-a-half day of free track time available. The first half day part was used for a pre-test to point out the manoeuvres and to plan the time schedule and the logistics for the actual test day. The remaining day was for the main test.

5.2 Manoeuvres

5.2.1 Cornering Manoeuvre

The manoeuvres should reflect the real world characteristics, so the first part of the test consists of a regular cornering manoeuvre. After examining the data during the pre-test, it appeared that the tightest corner of the track exposed the differences between the riders well, as a relatively tight corner requires resolute action on the controls.

The corner is part of a complete round which provides sufficient space to build up speed. The test section contains an approach lane, the actual corner and an exit lane. The corner is a 90° right hand turn. The inside corner radius is zero, but with a lane with of nine meter it is less tight as it may appear.

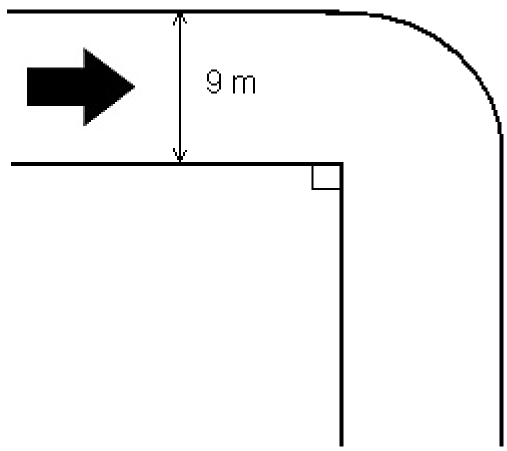

Figure 5.1: Cornering Manoeuvre

To expose certain tendencies, the manoeuvre should be challenging for all contenders. As the level of experience is very diverse among the riders this means that the manoeuvres have to build up in aggressiveness. As the track dimensions are fixed and the riders were free to choose their path throughout the corner, the remaining parameter to vary is velocity.

Due to time restrictions and the number of 10 test contenders, there was only sufficient time to perform the manoeuvre three times. The first round is used to get familiar with the track and the motorcycle. The second and third round were actually part of the test.

The first requirement was that the rider has to stay on track, within the borders of the lane. To expose the natural behaviour of the rider, they were allowed to use the full width of the track according to their own insight, but without cutting the edges of the corner. Whether this relatively great amount of freedom is justified, will be discussed at the end of the result sections.

The second requirement was to maintain a prescribed velocity as much as possible, as long as the riders were comfortable. In the first two rounds that was 50 km/h and in the third round 80 km/h.

So the strict requirements were:

1. Stay in the lane
2. Maintain the prescribed velocity as much as possible

5.2.2 Avoidance Manoeuvre

The second test element is the avoidance manoeuvre. Basically this is a single lane change manoeuvre with the difference that the riders receive a signal at the end of the entry lane whether to pass the obstacle along the right side or along the left side. This element of surprise is included in order to oppose to the fact that riders will prepare or settle for the manoeuvre. Also the input actions and output response will be more extreme, which might give more insight in the handling operation of the motorcycle.

The avoidance manoeuvre consists of three phases.

- First, the rider travels in a straight line at a constant prescribed velocity for a certain distance. This part is referred to as the entry lane.
- After some distance, the rider has to direct the motorcycle in lateral direction by a predetermined distance, called the offset.
- Finally, the motorcycle has to return to straight running in a line parallel with the entry lane at a certain lateral distance. This part is the exit lane.

This gives the manoeuvre as in Figure 5.2.

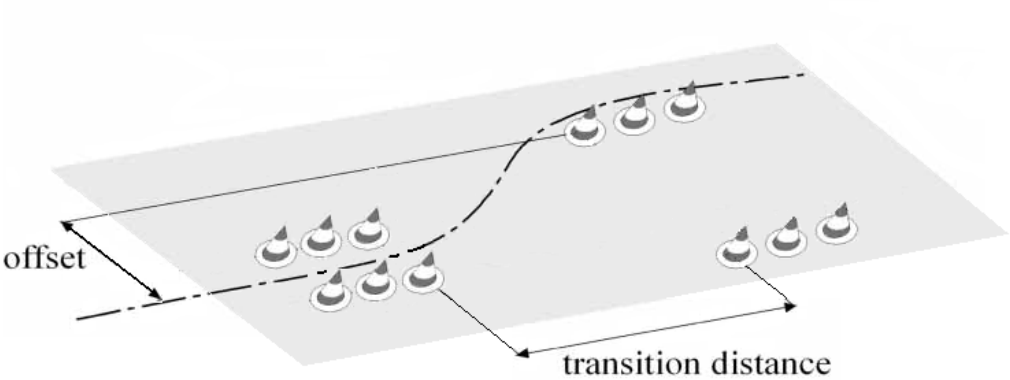

Figure 5.2: Avoidance manoeuvre [3]

During the test, variations were made with respect to the entry velocity and consequently the transition distance. Three tests are to be performed with a prescribed constant velocity of 50, 80 and 120 km/h. Due to the increasing velocity, the travelled distance during the riders reaction time increases. The travelled distance during the handling action itself increases too. The transition distances and obstacle dimensions (offset) are determined experimentally during a pre-test. It is possible to calculate the required dimensions, but doing this experimentally makes sure that the level of difficulty is within the comfort zone of the riders. The transition distances are determined to be 30, 50 and 80 m for respectively the 50, 80 and 120 km/h manoeuvres. In this way, the three tests have about the same level of difficulty. In all three cases, the offset is to remain constant and was set at 1.5 m. This results in 3 m for the total width of the obstacle. With a total lane width of 9 m, on both sides of the obstacle there is space for a smaller lane with a lane width of also 3 m. In this way, there is sufficient space for the rider to avoid the obstacle without running the risk of going off track. This gives the test set up as below in Figure 5.3 (not on scale).

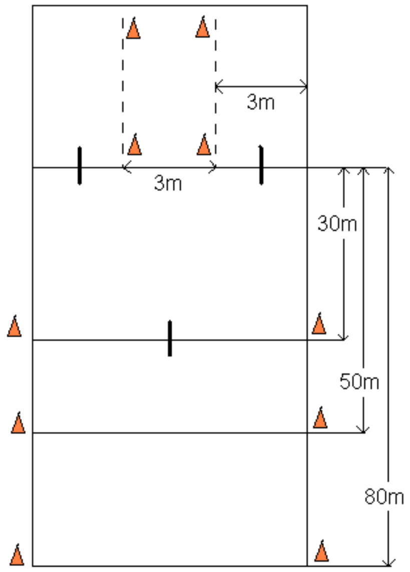

Figure 5.3: Avoidance Manoeuvre, test set up (not on scale)

The signals were given at the end of the corresponding entry lanes. To increase safety, the riders are required to pass the obstacle through the center of the small lanes next to the obstacle. This means they have to complete their actions before they arrive at the obstacle.

This gives the following set of requirements:

1. Avoid the obstacle
2. Pass the obstacle through the center of the lane
3. Maintain the prescribed constant velocity

5.3 EVALUATION QUESTIONNAIRE

Immediately after the riders have finished the manoeuvre, they have to evaluate their own performance. They have to rate and comment the physical and mental load they experienced. To do this in a structured way, an evaluation sheet is created, started from the principles of the Cooper-Harper method.

This method is used in the aviation industry by pilots to rate the performance of an aircraft during a specified manoeuvre. Using the Cooper Harper rating scale as discussed in the theory the pilot can reach four 'kinds' of quality:

a. Satisfactory
b. Tolerable
c. Unacceptable
d. Uncontrollable

By considering the following three decisions, the pilot will arrive at one of the four categories previously mentioned:

1. Is the vehicle controllable?
2. Is adequate performance attainable with a tolerable workload?
3. Is the vehicle satisfactory without improvement?

In our test, the riders will evaluate their own performance instead of the performance of the vehicle. Another difference is that the riders are unfamiliar with this sort of evaluation. Therefore, the performance criteria on which the rider has to consider the three above mentioned decisions have to be specified very precise. The rider has to understand the criteria, but he should also be able to monitor and asses the criteria while performing the test.

The performance criteria are linked with the set of requirements specified for each manoeuvre in the previous section. For the cornering manoeuvre the requirements were to stay in the lane and to maintain the prescribed velocity within the rider's comfort zone. The first requirement corresponds well with the first question whether the vehicle is controllable. The second requirement is used to determine the criteria for adequate and satisfactory performance. Adequate performance is obtained when the rider is capable of maintaining the prescribed velocity within a margin of 20 km/h. Satisfactory performance is obtained when the rider is able to maintain the prescribed velocity within a margin of 10 km/h. This gives the following set of questions:

1. Were you always in full control of the motorcycle?

2A. Were you able to maintain speed within +/- 20 km/h?

2B. Were you able to maintain speed within +/- 10 km/h?

On top of the evaluation of these performance criteria which the rider can answer with yes or no, the motivation of the riders is important. Therefore the riders are asked to assess their workload.

3. What was your workload?

The workload can be divided in physical and mental workload. The first one consists of steering and body movement. The second one consists of attention (on the road or on the display that has to be monitored) and stress or insecurity. This gives the following questions:

4. What was your physical workload?
    a. Steering
    b. Body Movement
5. What was your mental workload?
    a. Attention
    b. Stress/Insecurity

Finally the riders can declare if there is something that influenced their performance and if they are usually aware of their riding behaviour. This results in the evaluation sheet as in Figure 5.4.

Cornering 50

Rider: Age: No. years driving license (motorcycle): Riding frequency: Left or right handed:

1	Were you always in full control of the motorcycle?	Yes / No
2A	Were you able to maintain speed (50) within +/-20 km/h?	Yes / No
2B	Were you able to maintain speed (50) within +/-10 km/h ?	Yes / No

		Intolerable	Extensive	Considerable	Moderate	Low
3	What was your workload?	1	2	3	4	5

Workload in detail

		Intolerable	Extensive	Considerable	Moderate	Low
4	What was your Physical workload?					
	Steering	1	2	3	4	5
	Body movement	1	2	3	4	5

		Intolerable	Extensive	Considerable	Moderate	Low
5	What was your Mental Workload?					
	Attention	1	2	3	4	5
	Stress/insecurity	1	2	3	4	5

Extra

6 Were there things on the motorcycle or on the manoeuver that influenced your performance?

7 Are you usually aware of your riding behaviour, or does it go automatically?

FIGURE 5.4: EVALUATION FORM, CORNERING MANOEUVRE

The results of questions 1, 2A, 2B and 3 are used to come to a final rating according to the Cooper Harper Handling Qualities Rating Scale. Schematically the decision tree looks as follows, see Figure 5.5. The principle is basically the same as in the Cooper-Harper version. The only difference lies in the fact that the riders are offered a wider variety of choices at question 3. This results in a larger range at the scale. The decision tree with corresponding rates will not be shown to the riders, as this might affect their objectiveness.

Questions 4 and 5 offer a more detailed understanding of the workload that the rider is experiencing. It also helps the rider to come to a well considered rating for question 3.

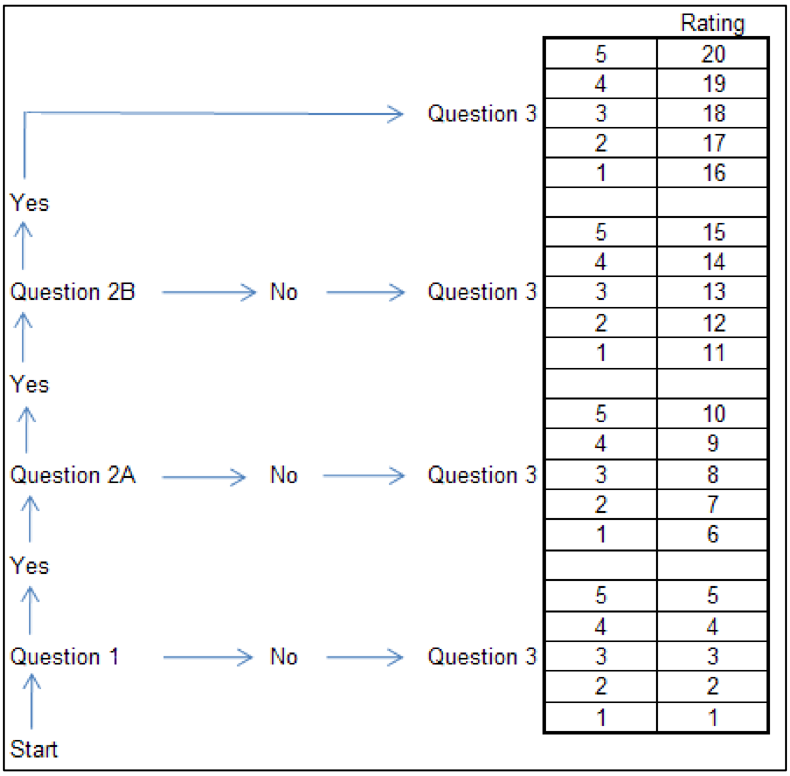

FIGURE 5.5: DECISION TREE

For the avoidance manoeuvre, only question 2 of the evaluation form is modified. The requirements were that the prescribed constant velocity should be maintained, the obstacle should be avoided and to pass the obstacle through the center of the lane. The first requirement on velocity should be no problem for all riders. The transition distance is adapted to the prescribed velocity, so for that reason this will not be a performance criterion. The last 2 requirements will be transformed into performance criteria as follows:

2A. Did you finish the manoeuvre before you arrived at the obstacle?

2B. Were you able to pass the obstacle through the center +/- 1 m?

For both evaluations holds that it will be important that the riders give comment on what they are doing and which difficulties they experience while performing the manoeuvre. Therefore they are encouraged to write down their detailed experiences in the empty boxes after each question.
In this way a comparison can be made between the rider's perception and the recorded data.

6 Results: Steering

A motorcycle rider has two ways of controlling the motorcycle during a turn. The first one is to apply a force on the handlebar, which results in a moment around the steering axis, the so called steering torque. The second one is to apply a moment directly in roll direction, basically by shifting body weight in lateral direction. This shift in body weight results in action and reaction forces in vertical direction on the handlebars, the footrests and the seat and in lateral direction at the contact points of the rider's knees at the tank. Together they form a roll moment, acting around the longitudinal axis of the motorcycle.
Apart from applying a roll moment, lateral body motion (or the lateral location of the centre of mass of the body) influences the moment that the rider has to apply around the steering axis. This has already been discussed in the theory.
In this chapter, the way a rider is operating a motorcycle will be described. During the main tests, two manoeuvres were defined with varying velocities. The riders had to perform an avoidance test and a general cornering manoeuvre.
In the next section, the general steering operation will be described using the data of the avoidance manoeuvre. After the general operation, different riders will be compared in riding style and efficiency. Also the influence of velocity will be referred to.
After that, the general cornering manoeuvre will be discussed according to the same themes as in the discussion of the avoidance manoeuvre.

The manoeuvres in the following sections are all performed on a closed track in Lelystad (The Netherlands), with the courtesy of The Dutch Police Academy. The track was situated in a open polder and during the test day there was a very strong cross wind that had its influence on the test. This influence will be indicated at places it may concern.

6.1 Avoidance Manoeuvre

The avoidance manoeuvre is basically a single lane change manoeuvre with the difference that the riders received a signal at the end of the entry lane whether to pass the obstacle along the right side or along the left side. This element of surprise was included in order to oppose to the fact that riders will prepare or settle for the manoeuvre. Also the input actions and output response will be more extreme, which might give more insight in the rider handling operation of the motorcycle.

6.1.1 Manoeuvre description

The avoidance manoeuvre consists of three phases.

- First, the rider travels in a straight line at a constant prescribed velocity for a certain distance. This part is referred to as the entry lane.
- After some distance, the rider has to direct the motorcycle in lateral direction by a predetermined distance, called the offset. This motion is initiated by a counter steering torque, accompanied by a moment in roll direction.
- Finally, the motorcycle has to return to straight running in a line parallel with the entry lane at a certain lateral distance. This part is the exit lane.

This gives the manoeuvre as in Figure 6.1.

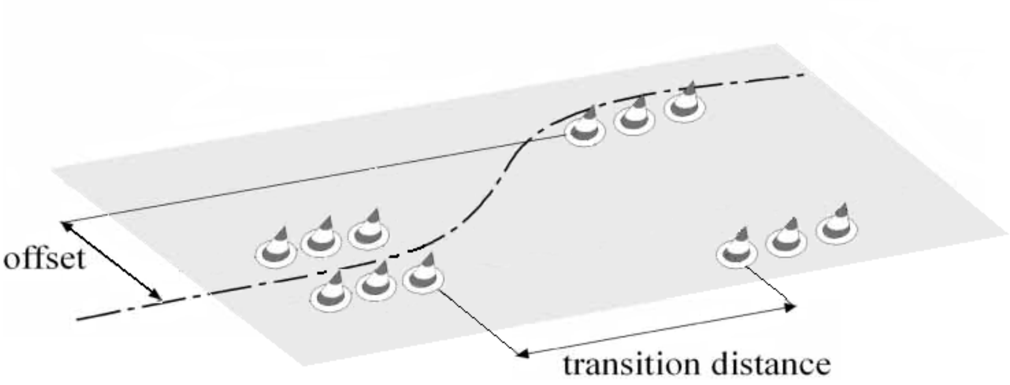

Figure 6.1: Avoidance Manoeuvre [3]

Three tests were performed with a prescribed velocity of 50, 80 and 120 km/h. The signals were given at the end of the corresponding entry lanes. Details on offset and transition distance can be found in section 5.2.2.

6.1.1.1 Rider Input and Rider/Motorcycle Response

Test Rider 1 will be used to demonstrate the characteristics of this manoeuvre. The next figure shows an avoidance along the right side of the obstacle (in opposite direction of Figure 6.1) with an entry velocity of 50 km/h, see Figure 6.2.

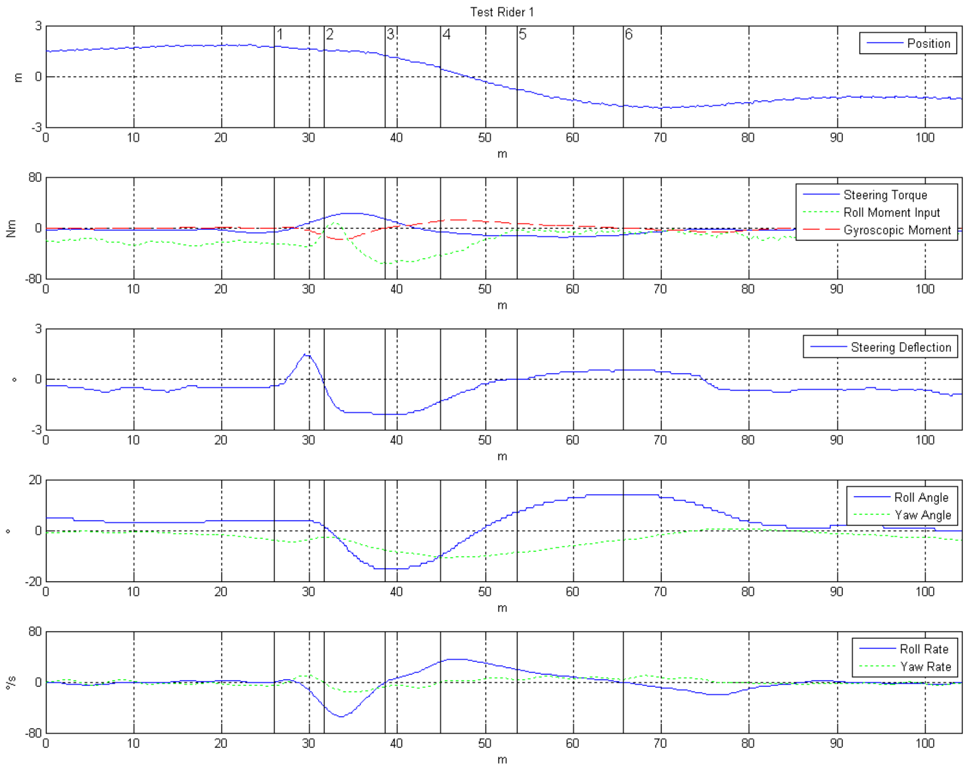

FIGURE 6.2: 50 KM/H AVOIDANCE MANOEUVRE BY TEST RIDER 1

The motion is initiated by a counter steering action. From point 1 on, the rider is applying a steering torque to the left in order to go right. This results in a steering deflection of 1.5° and consequently in a lateral force in left direction acting at the contact point of the front tire with the ground. This causes a yaw rate away from the intended heading, so called out tracking. This leads to a centrifugal force that acts on the motorcycle, that makes the motorcycle start to roll. This principle is demonstrated in Figure 6.3, again in opposite direction.

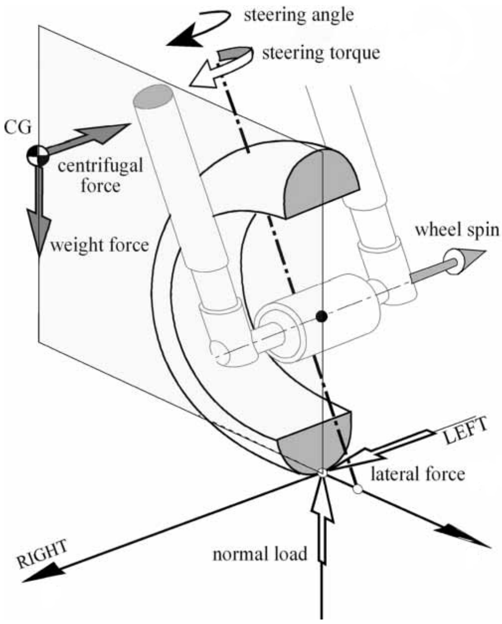

FIGURE 6.3: COUNTER STEERING INITIATION [3]

According to the theory there exists a gyroscopic moment at the instant of the initial counter steering, originating from the spinning of the wheel in combination with the flux of the steering deflection, prescribed by the following formula:

$$M_{G_\delta} = I_{w_f}\omega_f\dot{\delta}cos\varepsilon \tag{3.12}$$

With the parameters of the test motorcycle:

I_{w_f} = 0.47 kgm^2 and
ε = 25 °

During this manoeuvre the maximum value for M_{G_δ}=-4.70 Nm and is “helping” the motorcycle to roll. However, its contribution is rather small compared with the other moments in roll direction.
As the roll angle is highly increasing, a reaction moment can be observed in the resulting roll moment.

After the initial steering motion, the steering deflection rapidly changes sign and is directed to the right, point 2. At the same instant, the yaw rate changes direction to the right. From this moment on, the steering torque reaches its maximum and is still directed to the left. The new situation is as demonstrated in the next figure, Figure 6.4, again mirrored.

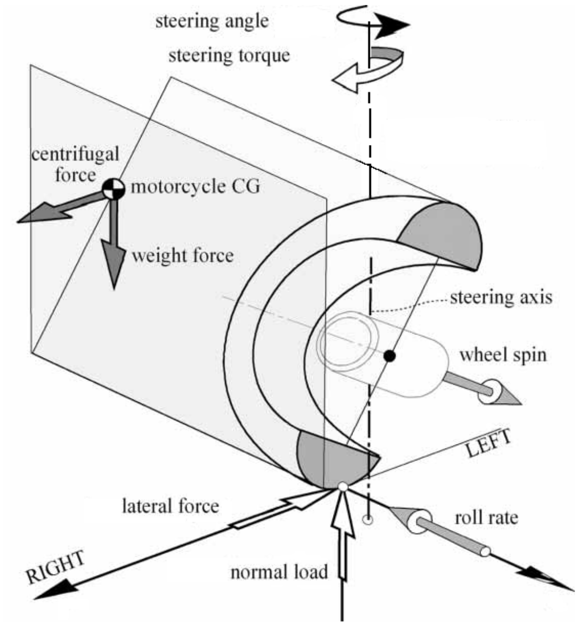

FIGURE 6.4: TURNING PART [3]

The component of the normal load causing a moment in steering direction is larger than the component of the lateral force causing a moment in counter steering direction. As a consequence, the rider has to block the handlebar from rotating further and must remain applying a counter steering torque.

As the steering torque starts to decrease, the steering deflection increases and so does the yaw rate. The centrifugal force becomes larger and this slows down the roll rate until the roll rate becomes zero and the maximum roll angle is reached, point 3. Also during this phase, the reaction moment in roll direction is clearly visible.
The motorcycle has a roll angle to the right but is rolling to the left. The steering deflection starts to rotate to the left and the yaw angle has reached its maximum at point 4. The steering torque has switched sign and the motorcycle is about half way the manoeuvre as the roll angle has passed through zero.
As the motorcycle starts to yaw to the left, the centrifugal force is pointing to the right. The roll rate in turn is slowing down while the roll angle towards the left is still growing. The steering deflection is also switching sign towards the left at point 5. From that moment on, the steering torque becomes smaller and as a consequence the steering deflection increases further. Finally at point 6, the motorcycle starts to roll back in upright position and the steering deflection returns to neutral. The exit lane is entered which concludes the manoeuvre.

It is remarkable that the resultant roll moment is never actually representing a rider action. It's graph only shows the reaction on the varying roll rate during the manoeuvre as it is almost in anti phase with the roll rate.

An important phenomenon that can be viewed in the figure but that has not been discussed in this detailed description is the gyroscopic effect originating from the roll velocity in combination with the rotational velocity of the front wheel. Projected around the steering axis this effect is prescribed by the following formula:

$$M_{G_\varphi} = -I_{w_f}\omega_f\dot{\varphi}\cos\varepsilon \tag{3.10}$$

With the parameters of the test motorcycle, this results in the plot as in Figure 6.2. From this figure it can be concluded that the main part of the steering torque input is required to counteract this gyroscopic effect.

6.1.1.2 Roll Moment Input

In this section the roll moment distribution with contributing factors will be further elaborated. The roll moment input is composed by the input following from the handle bar, the seat, the tank and the footrests.

Referring ahead to the section concerning general cornering, it will be shown that riders all have their particular way of using their body weight. Some riders decide to move their body weight inside the corner, others are placing their body to the outside part.

These intentional or unintentional decisions considering the lateral shifting of the body are disappearing as soon as the riders are forced to react rapidly on a occurring situation (in this case the signal). In Figure 6.5, the roll moment and the corresponding components are shown.

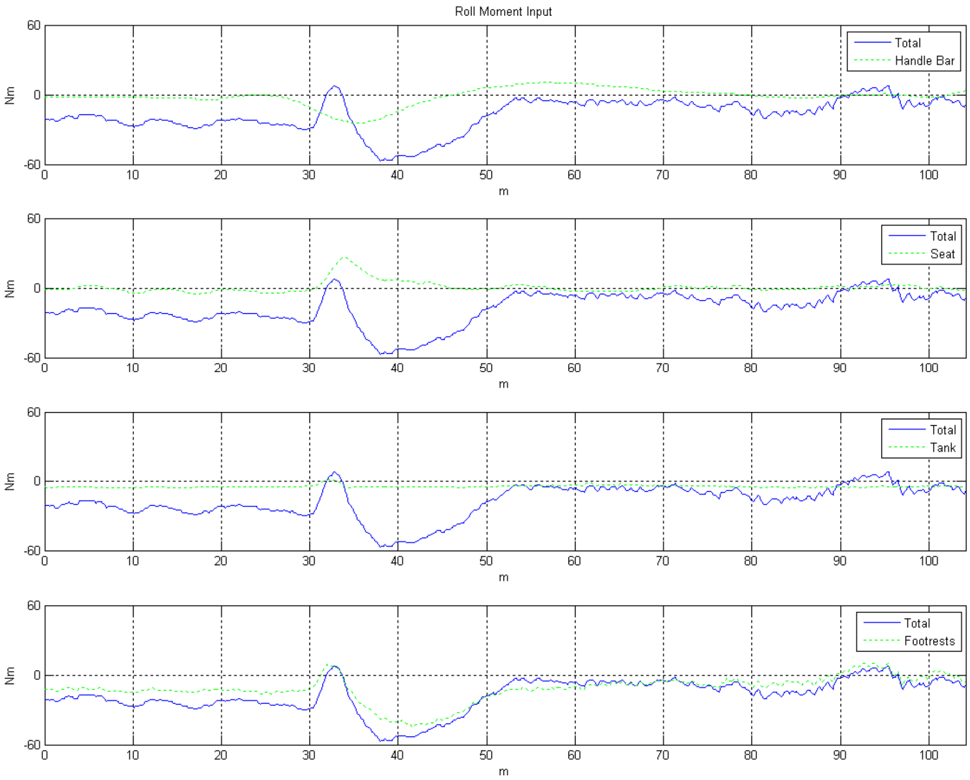

Figure 6.5: Roll Moment distribution with components, 50 km/h Avoidance Manoeuvre

The figure demonstrates that only the roll input on the handlebar is directed in the same direction as the roll velocity. This is a component of the total applied moment on the handlebar and 'mirrors' with the applied steering torque, see Figure 6.6.

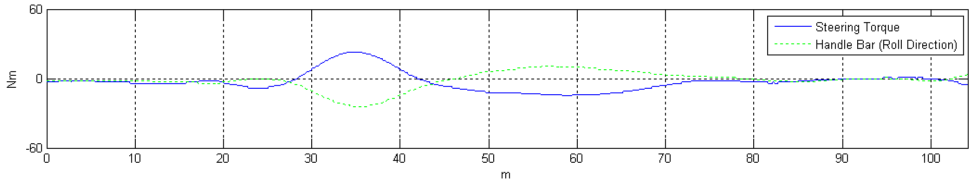

FIGURE 6.6: MOMENT COMPONENTS ON THE HANDLE BAR

The other three components are in counter direction with respect to the roll velocity. The video record that has been made indicates that those are reaction forces acting from the motor onto the rider, as the riders upper body is moving in counter direction too. If the rider was moving his upper body outwards to intentionally give an input, the data would have shown a moment in inward direction.

The contributing factors in roll direction partially balance as internal forces, but they do result in a moment in roll direction, acting on the motorcycle.

6.1.2 RIDER COMPARISON

Based on the characteristics found above, the riders performing the avoidance manoeuvre are compared. A total number of 8 riders will be compared, preliminary divided over three main categories:

1. Policemen
2. Test Riders
3. Beginners

To compare the rider categories in general, data will be used of riders who are representative for their category. In the next section, a qualitative comparison will be according to a similar plot as used in Figure 6.2. One section later, the handling efficiency will be addressed.

6.1.2.1 QUALITATIVE COMPARISON

As the manoeuvre is situated on a relatively small surface combined with the fact that the riders have little time to react on the signal, all riders fit the detailed description on rider input and rider/motorcycle response of the manoeuvre given earlier in this chapter in section 6.1.1.1. Therefore, the main focus will lie on the aggression that the riders put in their handling actions and the lateral motion of the upper body which is represented in the plot by the roll moment input. Any further differences will be referred to in the next section regarding handling efficiency. In this section, Policeman 1, Test Rider 3 and Beginner 4 will be compared performing a 50 km/h lane change manoeuvre, using Figure 6.7, Figure 6.8 and Figure 6.9.

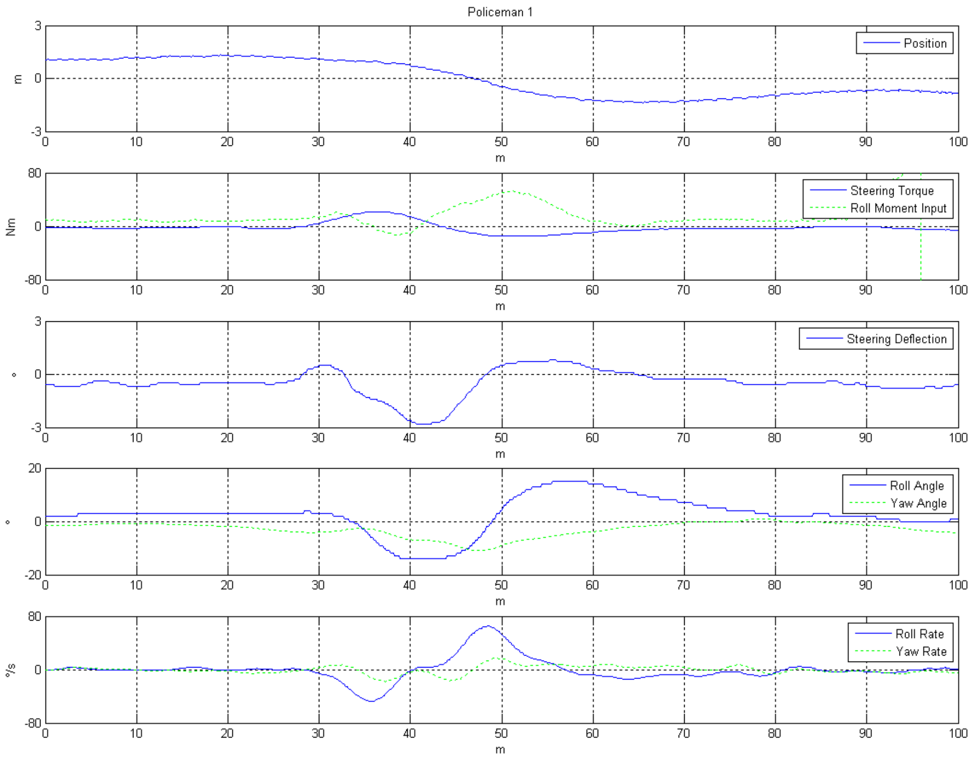

FIGURE 6.7: POLICEMAN 1, AVOIDANCE MANOEUVRE 50 KM/H

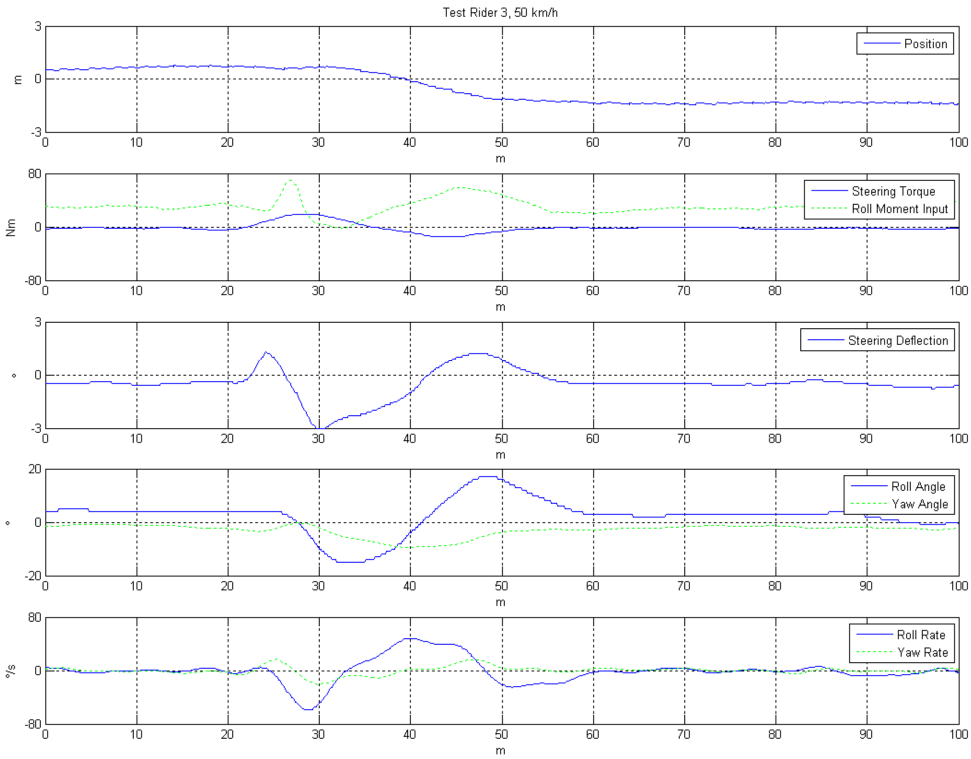

FIGURE 6.8: TEST RIDER 3, AVOIDANCE MANOEUVRE 50 KM/H

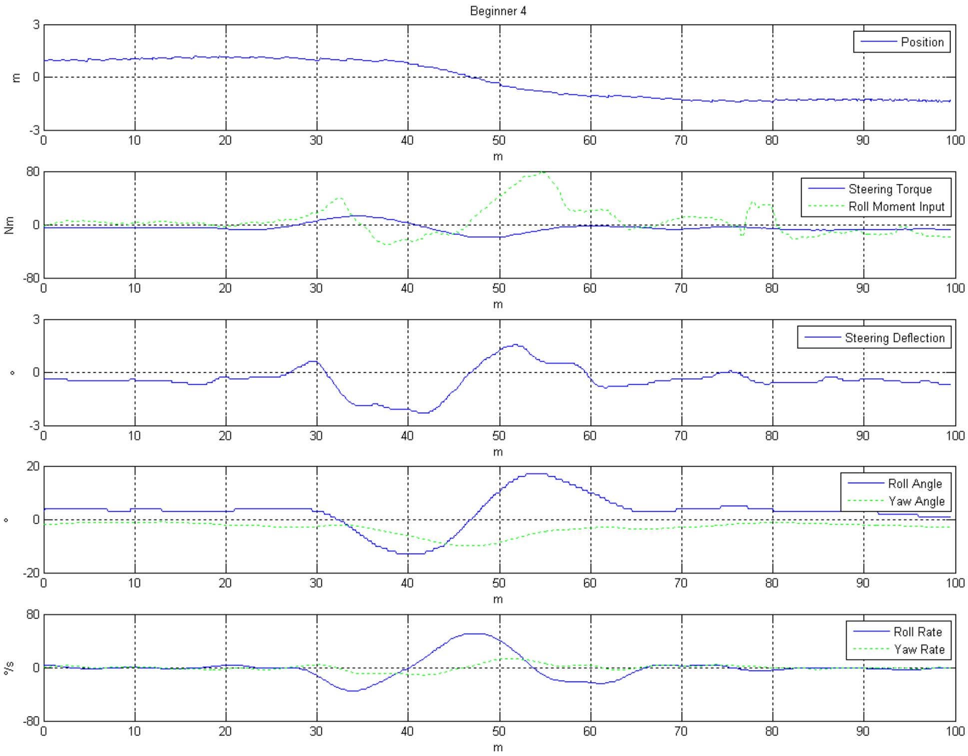

FIGURE 6.9: BEGINNER 4, AVOIDANCE MANOEUVRE 50 KM/H

After the riders have received the signal to pass the obstacle along the right side, all riders react with a counter steering torque. The test rider is more aggressive in applying this torque, which can be concluded from the steeper plot. This immediately results in a steeper and higher steering deflection to the left. The steering deflection causes the motorcycle to yaw to the left. The out tracking combined with the occurring centrifugal force acting to the right causes the motorcycle to roll to the right.

As a consequence of the initially more aggressive steering torque, all the above mentioned effects are stronger for the Test Rider, compared to the policeman and even more compared to the beginner. It results in a steeper and larger steering deflection, a higher yaw rate and consequently a higher roll rate.

From this point, a characteristic difference can be observed in the plot of the resultant rolling moment for the three riders. The plot for the test rider shows a large reaction peak, while this peak is not visible in the plot for the policeman. Apart from the higher roll rate (or roll acceleration) for the test rider this can be explained by regarding the connection between the rider and the motorcycle as a rotational mass spring system. In case of the Test rider this spring has a high stiffness. For this reason, as the motorcycle starts to roll, a strong reaction moment occurs from the motorcycle to the rider. This is similar for the beginner only less significant as his steering torque is less aggressive. For the Policeman on the other hand, this imaginary spring stiffness is very low and therefore there is almost no occurring reaction moment . This is confirmed by the videos which show that the Test rider after a small delay remains in the plane of symmetry with the motorcycle, while the policeman is moving away from the plane of symmetry. Policemen always have the tendency to remain in a vertical position. The (positive) effects of it will be referred to during the rider comparison of the cornering manoeuvre in section 6.2.2.1.

From the moment on that the roll rate changes sign to the left, both the policeman (at ± 42m) and the Test Rider (at ± 33m) move their upper body to the right, which creates a roll moment input to the left.

The video showed that the beginner does not move his upper body in lateral direction in this phase. Consequently, the line of the resultant roll moment is passing zero at the instant that the roll rate has its peak (at ± 47m). In case of the policeman and the Test Rider, this roll moment is actually helping the motorcycle to roll over, as it is applied during an increasing roll rate.

The remaining part of the manoeuvre does not show any significant differences. All riders conclude their manoeuvre mainly in the same way. Further differences are explained textual and in numbers in the next section.

6.1.2.2 Handling Efficiency

To quantify the efficiency of which the riders are operating the motorcycle during the avoidance manoeuvre, two modified versions of the Koch index will be used. Cossalter and Sadauckas introduced a modified version of the Koch Index, the Lane Change Roll Index:

$$Lane\ Change\ Roll\ Index = \frac{\tau_{\delta\ peak-peak}}{V_{avg} \cdot \dot{\varphi}_{peak-peak}} \left[\frac{N}{rad/s^2}\right] \quad (3.15)$$

This index is not satisfactory which leads to another modified version to fit the purpose of the test, comparing riders. A discussion about the motivation leading to this newly introduced index can be found in the Theory, in section 3.1.3.2.

$$New\ Lane\ Change\ Roll\ Index = \frac{\tau_{\delta\varphi\ peak-peak}}{V_{avg} \cdot \dot{\psi}_{peak-peak}} \left[\frac{N}{rad/s^2}\right] \quad (3.16)$$

For all the peak-to-peak values, the difference between the peak value in the first half of the manoeuvre and the peak value of the second half of the manoeuvre has been used as demonstrated in Figure 6.10.

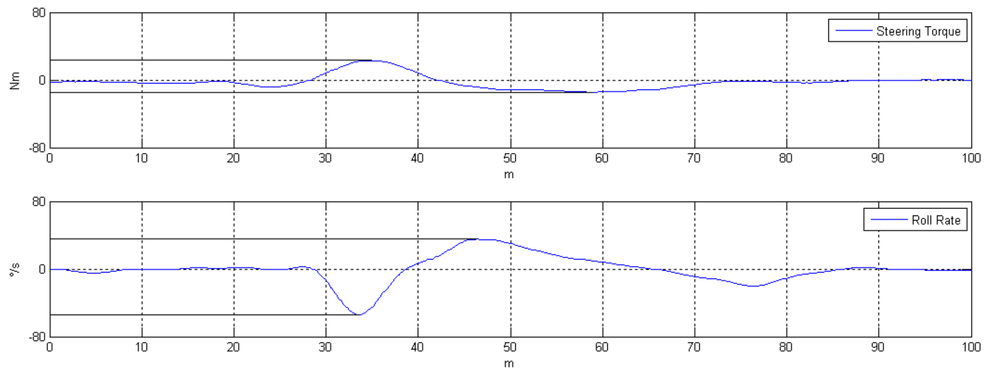

Figure 6.10: Estimation Peak values for Lane Change Roll Index

Both Cossalters index as the 'new' index are determined for the 50 km/h lane change and are listed together with the corresponding parameters in Table 6.1 respectively as LC_{φ} and LC_{ψ}. V_{avg} is given in m/s, $\tau_{\delta\ p-p}$ and $\tau_{\delta\varphi\ p-p}$ in Nm and $\dot{\varphi}_{p-p}$ and $\dot{\psi}_{p-p}$ in rad/s.

TABLE 6.1: LANE CHANGE INDICES WITH CORRESPONDING PARAMETERS, 50 KM/H AVOIDANCE MANOEUVRE

Rider	V_{avg}	$\tau_{\delta\ p-p}$	$\dot{\varphi}_{p-p}$	LC_{φ}	$\tau_{\delta\varphi\ p-p}$	$\dot{\psi}_{p-p}$	LC_{ψ}
Policeman 1	14.24	36.9	1.95	**1.33**	63.1	0.61	**7.22**
Test Rider 1	14.79	37.9	1.57	**1.63**	51.0	0.46	**7.47**
Test Rider 2	13.14	23.7	1.01	**1.79**	32.3	0.38	**6.55**
Test Rider 3	13.48	34.3	1.85	**1.37**	48.3	0.65	**5.48**
Beginner 1	13.57	32.6	1.51	**1.59**	44.9	0.47	**7.04**
Beginner 2	13.00	30.6	1.16	**2.02**	48.2	0.38	**9.65**
Beginner 3	12.38	26.0	1.39	**1.51**	41.0	0.45	**7.42**
Beginner 4	13.85	32.1	1.51	**1.53**	54.7	0.44	**9.06**

For convenience, the results for both indices are also plotted in a figure by rider category, showing the minimum, maximum and mean value, see Figure 6.11. Having a look at the right figure and at the last column of the table, the test riders are performing relatively well, in particular Test Riders 2 and 3. The beginners are performing worse, beginner 2 and 4 in particular.

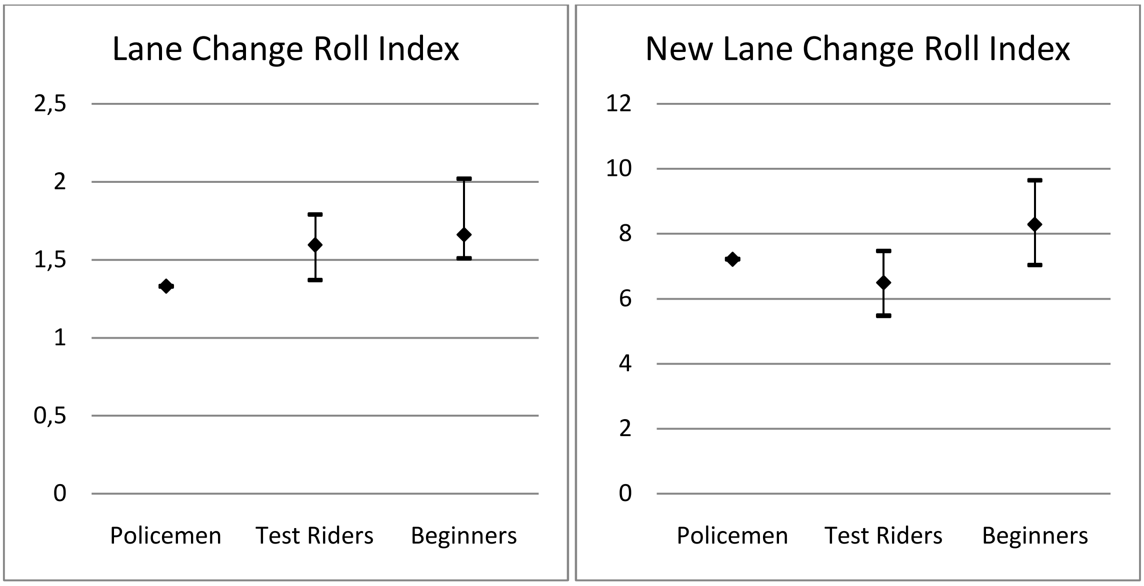

FIGURE 6.11: LANE CHANGES INDICES, 50 KM/H AVOIDANCE MANOEUVRE

Isolating Test Rider 2 and Beginner 2 for comparison, it is clear that Beginner 2 uses almost 50 % more input moment on the steering bar to obtain the same yaw velocity as Test Rider 2. Selecting Test Rider 3, this rider accomplishes a much higher yaw rate using the same input as Beginner 2. Further investigation of the data gives the possible causes for these differences.

The first cause for the differences in the riders efficiency may be found in the ratio between the moment on the steering bar in roll direction τ_φ and the steering torque τ_δ at the instant of the two input peaks. The second cause is related with the 'steering aggressiveness', the steering torque rate $\dot{\tau}_\delta$. For both characteristics the peak to peak values are used again for determination. For the four highlighted riders they are listed in Table 6.2.

TABLE 6.2: CHARACTERISTICS OF SELECTED RIDERS

Rider	LC_ψ	τ_φ/τ_δ	$\dot{\tau}_\delta$
Test Rider 2	6.55	1.20	75.8
Test Rider 3	5.48	0.95	106.3
Beginner 2	9.65	2.08	75.2
Beginner 4	9.06	2.38	87.6

Referring ahead to the section about general cornering, it will be shown that moments applied in roll direction only have a modest contribution in actually changing direction. The ratios in this table confirm that assumption. Both beginners show a large contribution in roll direction and consequently their efficiency is low compared with the Test Riders.

During a lane change, there are two instants at which the sum of all moments acting on the motorcycle influencing the steering torque are relatively low. The first is during the entry at which the motorcycle is straight up without rotational velocities, the second time (but less significant) is when the motorcycle has reached its maximum roll angle when the roll velocity is zero. In turns out that the peaks in the steering torque rate coincide with both these instants. An aggressive rider, in this case Test Rider 3, may benefit from this fact as his steering torque is relatively large at that time. However, apart from these numbers there is no hard evidence traceable in the data to confirm this theory.

Comparing both lane change indices in Table 6.1, the first thing that appears immediately is the difference between both indices in general. The roll rate is about three times higher than the yaw rate. Combined with the difference between the steering torque and the total moment on the steering bar, the indices are of a different order of magnitude.
Besides this general difference, it also shows that the mutual proportions are different too. For example, Test Rider 2 is performing well regarding the 'new' lane change index LC_ψ, but has a low efficiency according to the lane change index LC_φ. One explanation for this lies in the relation between the roll rate and the yaw rate. Naturally the yaw rate is highly affected by the roll rate, but from the data it follows that a higher roll rate does not necessarily result in a higher yaw rate (relatively). However, the main cause for the difference lies on the input side of the indices. Regarding only the steering torque τ_δ as in the original lane change index, only a part of the total input on the handlebar is considered which gives a different view on efficiency.

Both indices show about the same spreading in results per category. Not a lot of persons contended the test, so based on that it is not possible to make a proper judgement on which index has a preference. However, the lane change roll index LC_φ may give a clear view on agility performance of the motorcycle, in this investigation riders are compared instead of motorcycles and preference goes out to the 'new' lane change index LC_{ψ}.

An attentive reader may have noticed that one rider is missing in the results of this manoeuvre. Policeman 2 disregarded the given signals and therefore the results were not useful as the "surprise effect" was not present.

The second thing that is missing in this efficiency comparison is the 80 and 120 km/h version. The yaw rate becomes low as the velocity is increasing. Due to the high cross wind the data for the yaw rate was fluctuating around the already small value. This made it impossible to accurately determine the peak values.

6.1.3 Manoeuvre Comparison

As mentioned before, this manoeuvre was also performed with an 80 and 120 km/h velocity. In a general sense, the stepwise explanation of the 50 km/h lane change holds, but there are some differences. The 50 and 120 km/h lane change will be used to demonstrate this, see Figure 6.12 and Figure 6.13.

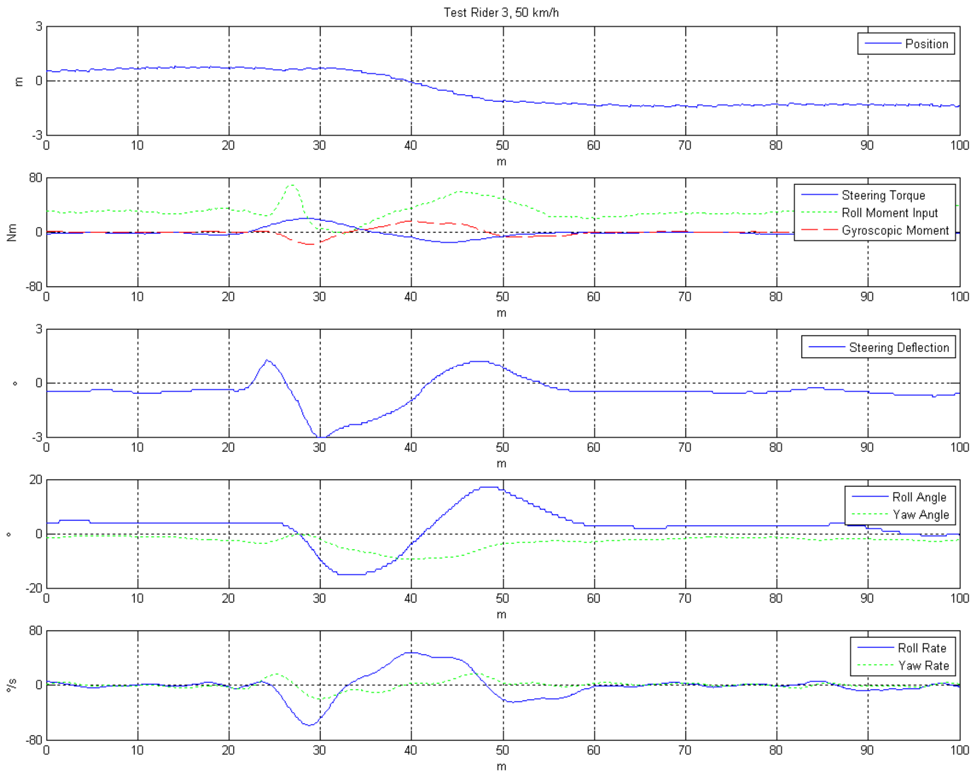

Figure 6.12: Test Rider 3, Avoidance Manoeuvre 50 km/h

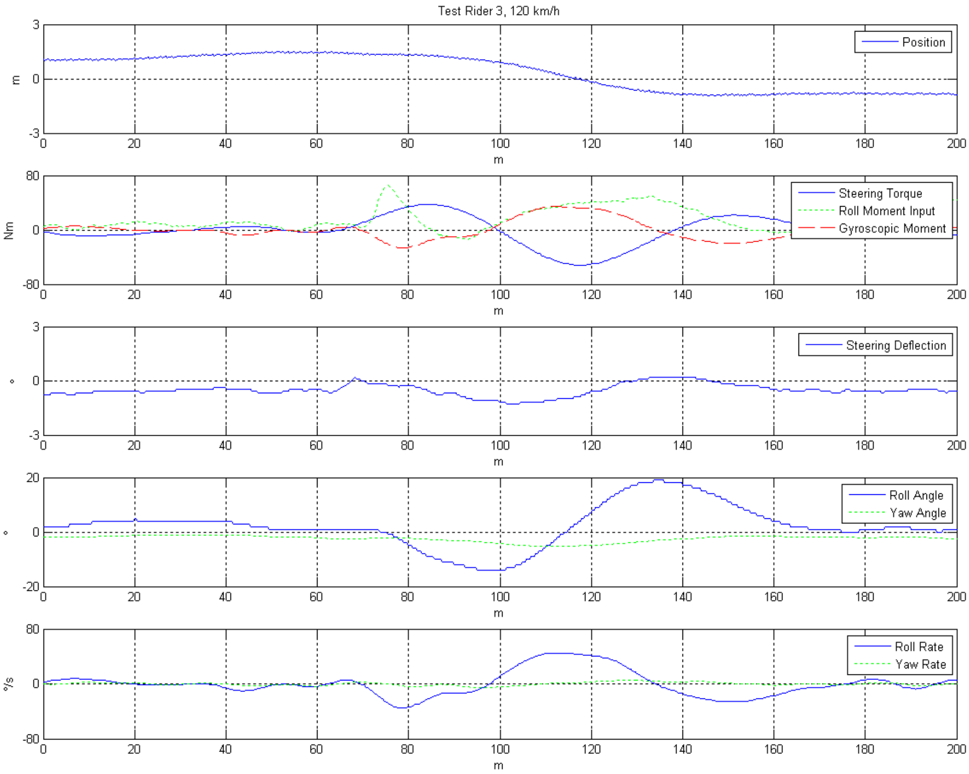

FIGURE 6.13: TEST RIDER 3, AVOIDANCE MANOEUVRE 120 KM/H

Initially, the manoeuvre starts with a counter steering action. As a consequence, the motorcycle starts to yaw in counter direction (left) with respect to the intended heading. Due to the occurring centrifugal force, the motorcycle starts to roll to the right. This is the same as during the 50 km/h lane change.

From the moment on that the steering deflection changes sign, almost immediately the roll rate has its peak. This is earlier than during the 50 km/h lane change at which the roll rate was still growing. Due to the high velocity and consequently the high centrifugal force that occurs after the steering deflection changes direction to the right, the roll rate decelerates almost instantly.

This phenomenon holds for all riders. The peak in roll rate comes relatively earlier in the manoeuvre and at the same time, the steering bar remains longer deflected in counter direction before it changes sign to the intended heading. This will be demonstrated at the end of this section.

The motorcycle reaches the maximum roll angle to the right and starts to roll to the left. The steering deflection starts to rotate to the left and the yaw angle has reached its maximum. The maxima of the steering deflection and the yaw angle are closer to each other, compared to the 50 km/h manoeuvre .

As the motorcycle starts to yaw to the left, the roll rate has its peak and decelerates until also the roll angle has its peak. From this moment on the motorcycle returns to upright position, which concludes the manoeuvre.

Apart from the qualitative differences, there are differences in magnitude regarding all parameters. ‘The input is higher while the output is lower’. Starting with the last one, Figure 6.13 demonstrates

that both the roll angle as the yaw angle with corresponding roll rate and yaw rate become lower as the velocity is increasing. Also the steering deflection is significantly lower.
On the input side, the steering torque is larger as the velocity increases. This is due to the fact that the gyroscopic effect increases linearly with velocity. And from the figure it follows that the majority of the steering torque is required to counteract this effect.

A way to find statistical trends in large data sets is to determine the correlation coefficient. Depending on the covariance C of two or more changing variables, the correlation coefficient R is defined in the following way:

$$R(i,j) = \frac{C(i,j)}{\sqrt{C(i,i)C(j,j)}} \tag{6.1}$$

Multiple parameters are mutually compared during a specified range. The program, in this case Matlab, returns a number between minus one and one. The correlation coefficient does not give any information about the relation itself, but performing this action more than one time with for example different riders or different velocities, trends may appear that one could overlook otherwise. The next figure represents the correlation coefficients of the steering torque and the steering deflection, see Figure 6.14. A correlation coefficient of 1 would mean that both curves in the plot have an identical shape. A coefficient of -1 would mean the same shape, but negative relation.

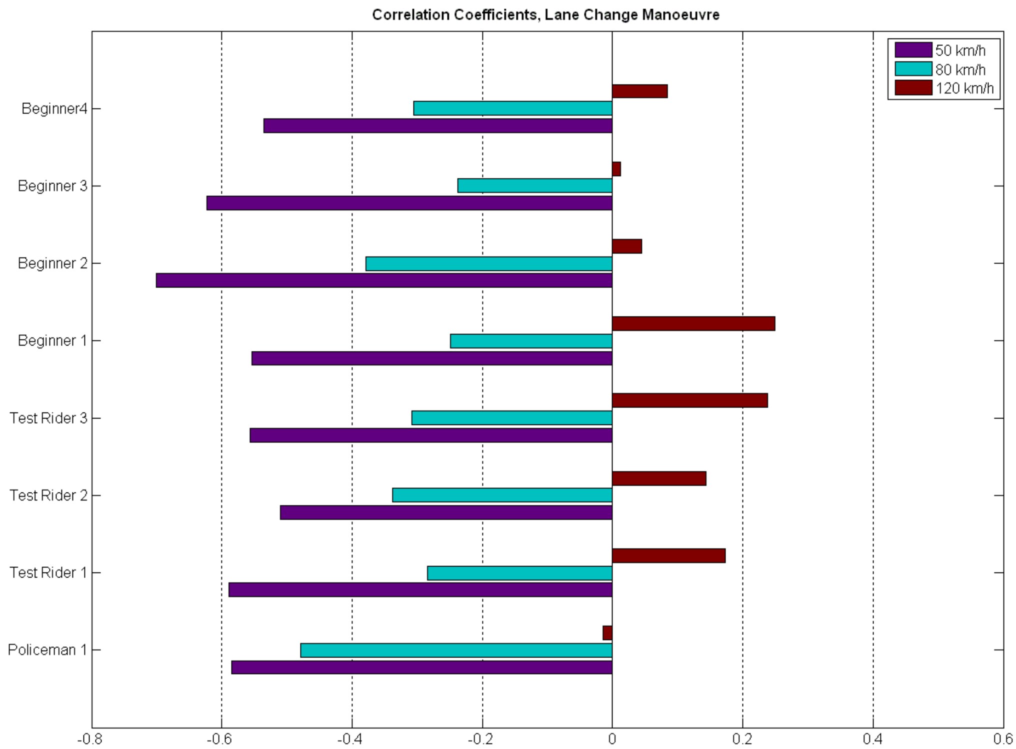

FIGURE 6.14: CORRELATION COEFFICIENTS OF STEERING TORQUE AND STEERING DEFLECTION, AVOIDANCE

It follows that for all riders, the coefficient changes from negative to slightly positive as the velocity increases from 50 to 120 km/h. It means that the steering torque becomes more directed in the direction of the steering deflection i.e. less counter steering.

6.1.4 Summary

In this first part of the results, the general steering operation of a motorcycle has been described demonstrating an avoidance manoeuvre. After that, different riders are compared with respect to their riding style and steering efficiency. Also the influence of velocity is referred to.

When a rider is entering a turn, the motion is initiated by a counter steering action. The rider applies a steering torque which results in a steering deflection. Consequently, a force in lateral direction is acting at the contact point of the front tire with the ground. This causes a yaw rate away from the intended heading, so called out tracking. This leads to a centrifugal force acting on the motorcycle, that makes the motorcycle start to roll.
Once the motorcycle start rolling, the steering deflection changes sign to the intended heading and at the same time the yaw rate changes sign too. The rider maintains the counter steering torque, as he is preventing the handlebar from rotating further due to the acting forces.

Two types of gyroscopic moments exist during the corner entry. Only the effect originating from the roll velocity in combination with the rotational velocity of the front wheel plays an important role and requires the majority of the applied steering torque.
The other gyroscopic moment originating from the velocity of the steering deflection in combination with the rotational velocity is rather small. The assistance that this moment provides during corner entry is negligible.
When the manoeuvre was performed with a higher velocity, the steering deflection became smaller. Also the roll and yaw angle with corresponding roll and yaw rate decreased. The steering torque increased due to the fact that the gyroscopic moment increased linearly with velocity.

During the avoidance manoeuvre, mainly all moments in roll direction are reaction moments from the motorcycle to the rider. The reaction moments for the policeman are smaller with respect to the test rider and the beginner as the policeman's upper body is connected with the motorcycle like a 'low stiffness spring'.

Relating the rider input with the rider/motorcycle response, the test riders were most efficient and the beginners were least efficient. The difference was mainly caused by the fact that beginners apply a lot of force on the handlebar directly in roll direction. This appears to be inefficient. Another possible cause is that the test riders were more aggressive in applying the steering torque, but the data did not supply sufficient prove to confirm this theory.
The results within the beginner category were very divers, which means that there is no stereotype beginner.
To compare the efficiency of riders, an existing index to determine the agility of a motorcycle, the Lane Change Roll Index, is modified to be used to compare the riders in their handling efficiency. This new index gave better results relating more relevant input and output for this subject than the standard version.

6.2 Cornering Manoeuvre

The cornering manoeuvre is a simple basic manoeuvre in which the rider was free to choose the path of his preference, within the lane dimensions.

6.2.1 Manoeuvre description

The particular right hand turn was a 90° corner with an inside radius of 0 meter. The lane width was 9 meter, so with the liberty of taking his own path, this turn was less sharp as it may seem at first sight, see Figure 6.15.

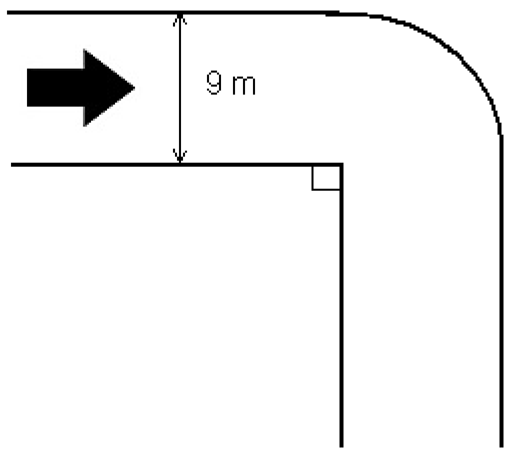

Figure 6.15: Cornering Manoeuvre

The manoeuvre has been performed twice. One time with a prescribed velocity of 50 km/h and once with 80 km/h. A detailed description of this test can be found in the section 5.2.1.

6.2.1.1 Rider Input and Rider/Motorcycle Response

Test Rider 1 will be used again to demonstrate the characteristics of this manoeuvre. The next figure shows the cornering manoeuvre with an entry velocity of 50 km/h, see Figure 6.16.

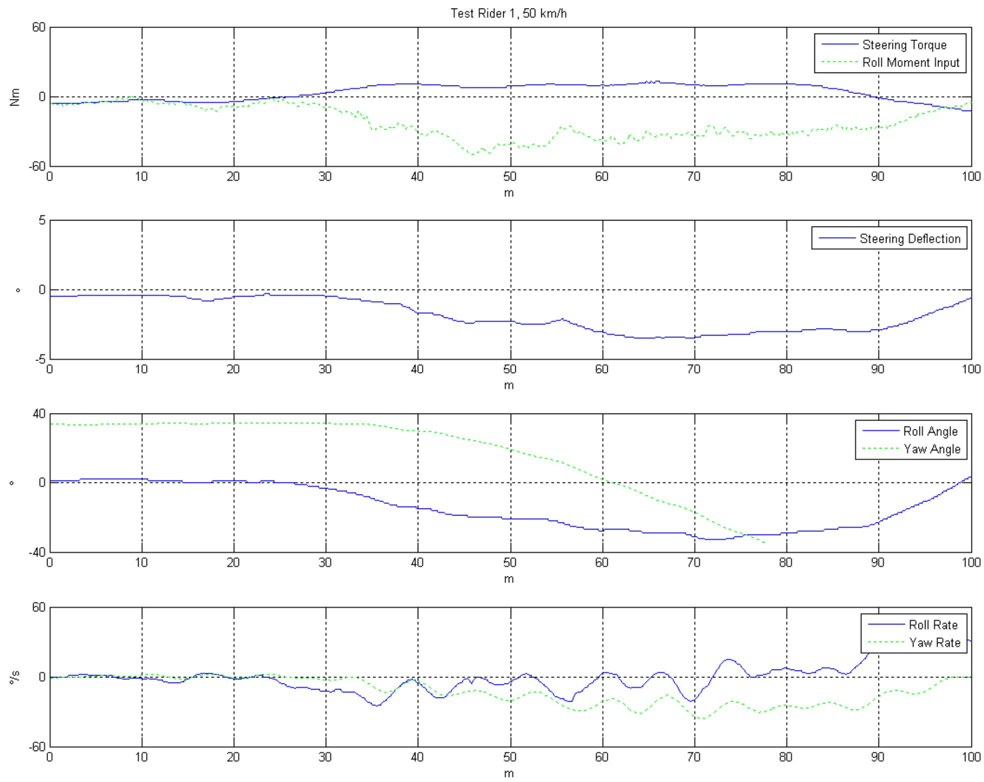

FIGURE 6.16: 50 KM/H CORNERING MANOEUVRE BY TEST RIDER 1

When entering a corner, the rider gives a steering torque in opposite direction. Usually, this results instantly in a steering deflection in the direction of the applied steering torque but this is hardly traceable in the plot. As demonstrated in the avoidance manoeuvre, this initial steering deflection makes the motorcycle yaw away from the intended heading. During this cornering manoeuvre, also that aspect is not confirmed strongly. As this is not a tight and demanding manoeuvre, characteristics as in the avoidance manoeuvre are not recognizable in the figure. The motorcycle just needs a small amount of input to make it “capsize” in the intended direction.
The motorcycle starts to roll in the direction of the corner. Once the motorcycle is rolling, the steering deflection starts to turn into the roll direction. Both the roll angle and the steering deflection increase slowly. The roll angle has its maximum right after the yaw rate has reached its maximum at around 72 m. From that moment on, the centrifugal force becomes too large and forces the motorcycle to roll back. Along the complete range, the steering torque remains in counter direction to block the handlebar from deflecting further

The roll moment input on the whole range is directed into the corner, but at this point the impact or consequences of it is difficult to describe. However, there is an interesting peak visible which corresponds with a similar peak in the steering deflection curve. Also at the same instant, a sudden increase in roll angle can be observed. A decrease in roll moment cannot lead to an increase in roll angle. The other way around; a sudden increase in roll angle causes a reaction in the roll moment. In turn, the sudden increase in roll angle is caused by the decrease in steering deflection. The decrease in steering deflection is most likely due to a bump in the road, as there was a transition of road surfaces at that location.

6.2.1.2 Roll Moment Input

As mentioned before, the Roll moment input is composed by the input following from the handle bar, the seat, the tank and the footrests. In Figure 6.17, the roll moment distribution and components are displayed in one plot. The components are displayed separately, but in all sub-plots the graph of the total roll moment is shown.

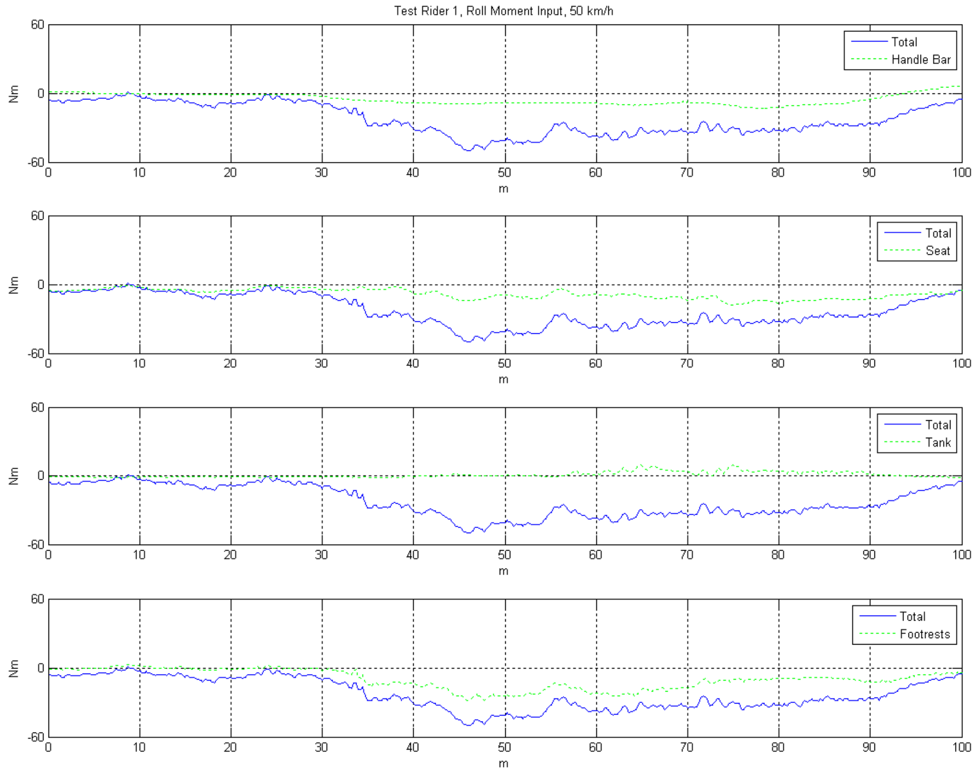

Figure 6.17: Roll Moment distribution with components, 50 km/h Cornering Manoeuvre

Although the roll moment is mainly caused by the motion and the location of the centre of gravity of the upper body, it is interesting to see that, for this rider, the moment originating from the footrests is the major contributor. Despite of the upper body moving laterally, the contribution of the moment of the tank is modest or almost negligible.

The force on the handle bar is a component in vertical direction of the resultant force on the handle bar and mirrors again with the steering torque.

6.2.2 Rider Comparison

Based on the characteristics found above, the riders performing the cornering manoeuvre are compared. A total number of 9 riders will be compared, preliminary divided again over three main categories:

1. Policemen
2. Test Riders
3. Beginners

To compare the rider categories in general, data will be used of riders who are representative for their category.
Beforehand, the policemen are known to have a different riding style as they prefer maximum control at all times above efficiency. It will be interesting to see whether this will be noticeable in the data.
In the next section, a qualitative comparison will be according to a similar plot as used in Figure 6.16. One section later, the handling efficiency will be addressed.

6.2.2.1 Qualitative Comparison

In this section, illustrative datasets of each rider category will be compared using the right hand turn with an approach velocity of 50 km/h, as in the previous section.

Generally, all riders fit the description as in section 6.2.1.1. The main difference is related with the usage of the upper body, which is largely represented by the roll moment input graph. Test Rider 1 moved inwards and applied a roll moment into the corner on the complete range, see Figure 6.18. As mentioned before, policemen have a different riding style. During a turn, the rider transfers his centre of gravity out of the corner by moving the upper body outwards. At the instant this motion is initiated, this would result in an impulse into the corner, but after that it gives a moment to the outside as the rider has to balance himself. This is confirmed in the plot for the policeman in Figure 6.19.

The graph for the roll moment of the policeman is slightly confusing as it seems to conflict with the text above. This can be explained by the fact that there was a strong cross wind from the left side of the approach lane. The test rider is counteracting by applying a steering moment to the right, while the policeman is applying a roll moment to the left. This is not necessarily illustrative for that type of rider, but should not be unremarked.

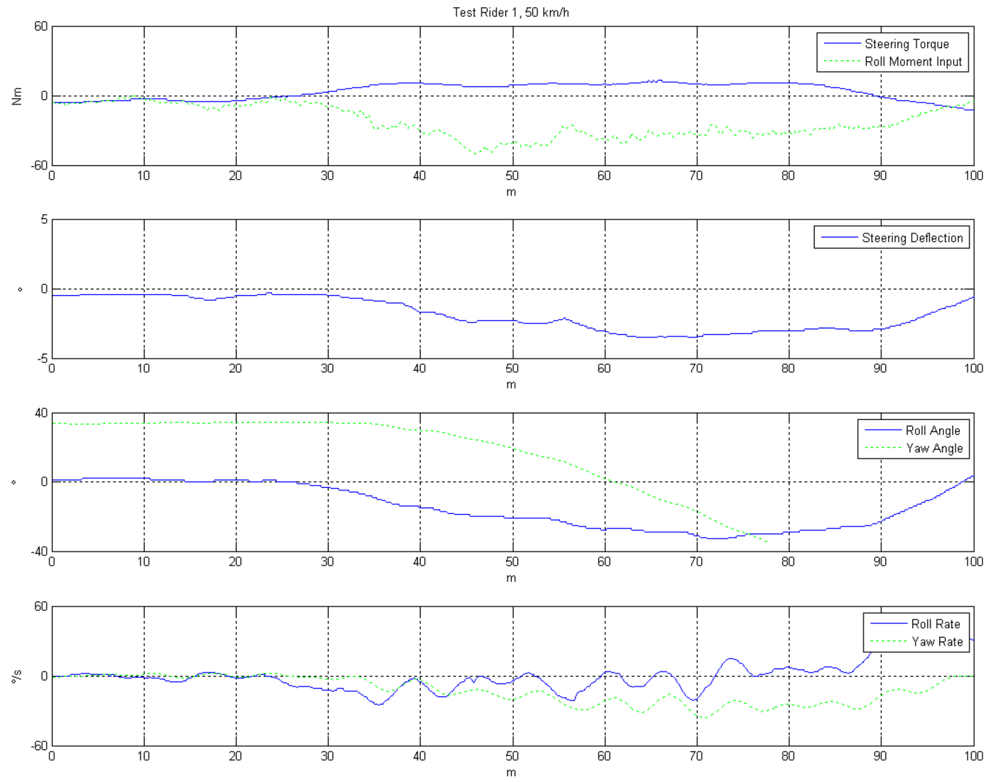

FIGURE 6.18: TEST RIDER 1, CORNERING MANOEUVRE 50 KM/H

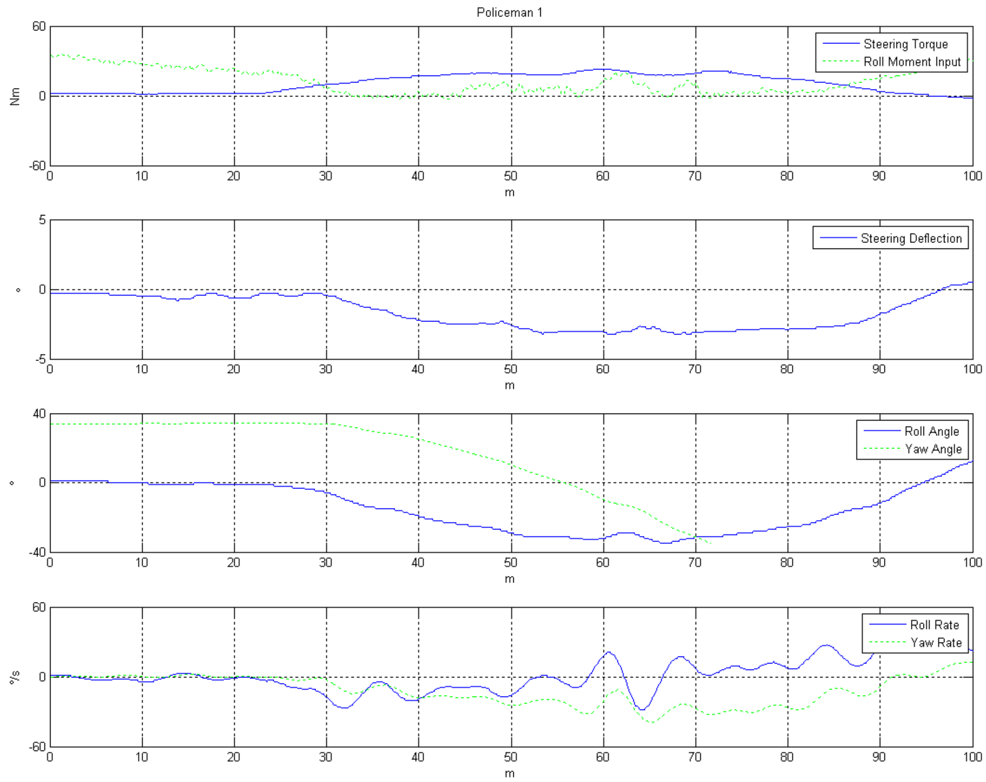

FIGURE 6.19: POLICEMAN 1, CORNERING MANOEUVRE 50 KM/H

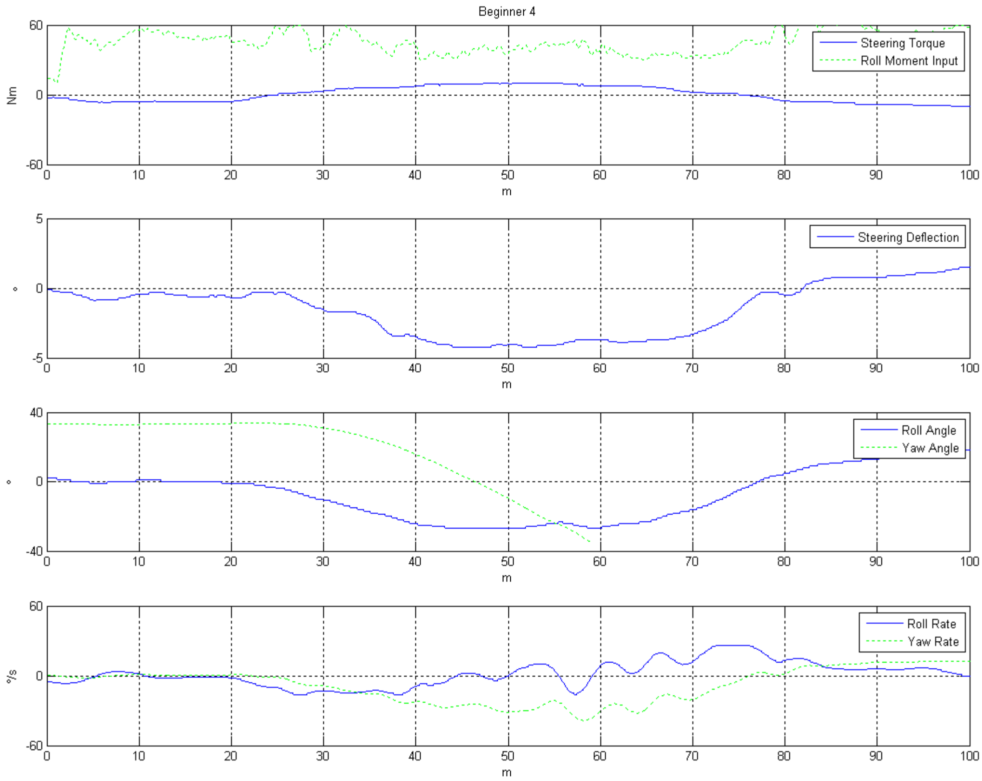

FIGURE 6.20: BEGINNER 4, CORNERING MANOEUVRE 50 KM/H

It is clear that the test rider has a roll moment resulting inside the corner and that the policeman and the beginner have a resulting moment neutral or outside the corner. According to the theory, this should affect the steering moment. As the rider is maintaining his upper body in a relatively upright position, the motorcycle is pushed down more. This way of cornering requires a larger steering moment and this is confirmed in the plot for the policeman.
This theory does not hold for the plot for the beginner, Figure 6.20, as his steering torque is still relatively low. However, all beginners had a lower entry velocity, so this comparison is not entirely justified.

Together with the roll moment distributions being different, the roll moment compositions are also different. While the test rider is having all roll moment components in the same inward direction, see Figure 6.21, the policeman only has the contribution of the handlebar in inward direction, see Figure 6.22. This way of steering is characteristic for policemen. Pushing the motorcycle down by hand gives reaction forces at the other contact points with the motorcycle.

Transferring the upper body to the outside, results in a more stable steering behaviour. The motorcycle roll angle is increased and as a consequence the steering deflection decreases. This results in the fact that during the turn, the centrifugal force has a smaller component in the spinning direction of the front wheel. Especially at low velocities or small corner radii, this component creates a feeling of unbalance. So despite of the fact that it results in a larger required steering torque, it gives more control. Another positive effect of staying in an upright position, is the better survey.

The beginner is putting a lot of force on the handle bar and the footrests, see Figure 6.23. Basically the input moment on the handlebar is completely neutralised by the moment on the footrests. This holds also for the policeman.

Although the distribution is very diverse, it appeared that all beginners are giving a large input directly in roll direction.

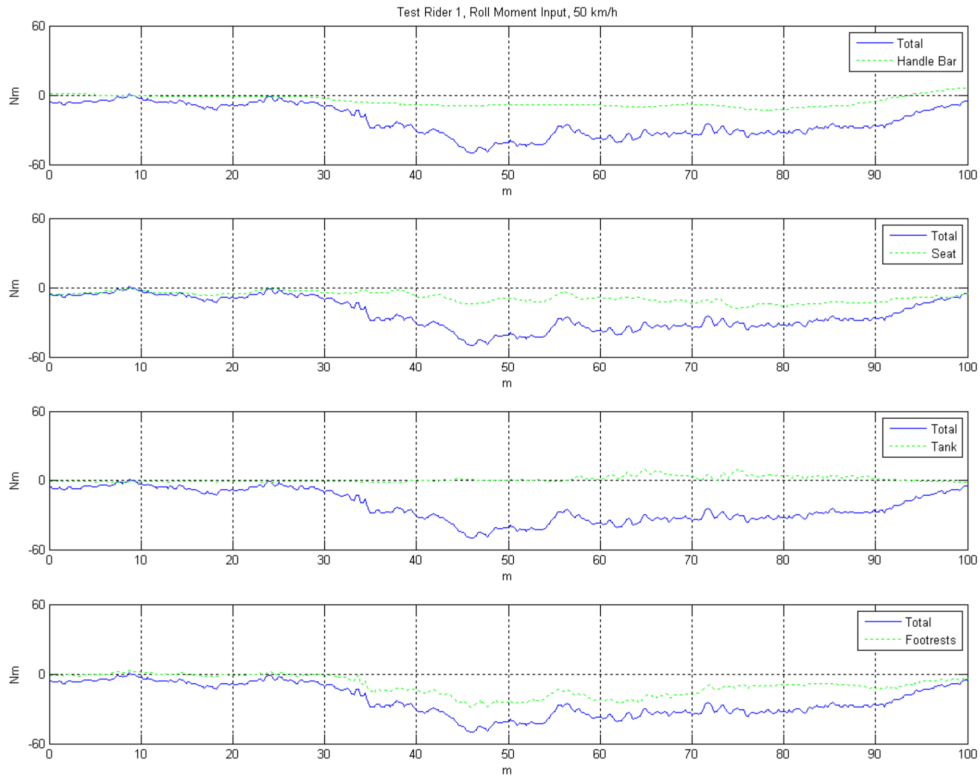

FIGURE 6.21: ROLL MOMENT DISTRIBUTION WITH COMPONENTS, TEST RIDER 1

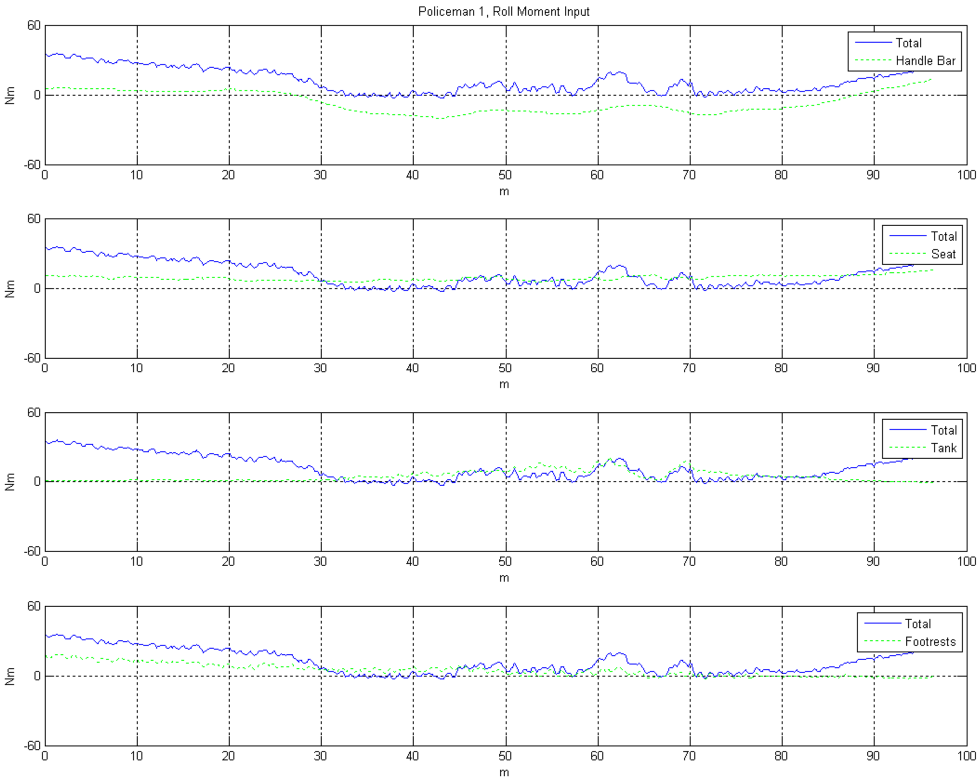

FIGURE 6.22: ROLL MOMENT DISTRIBUTION WITH COMPONENTS, POLICEMAN 1

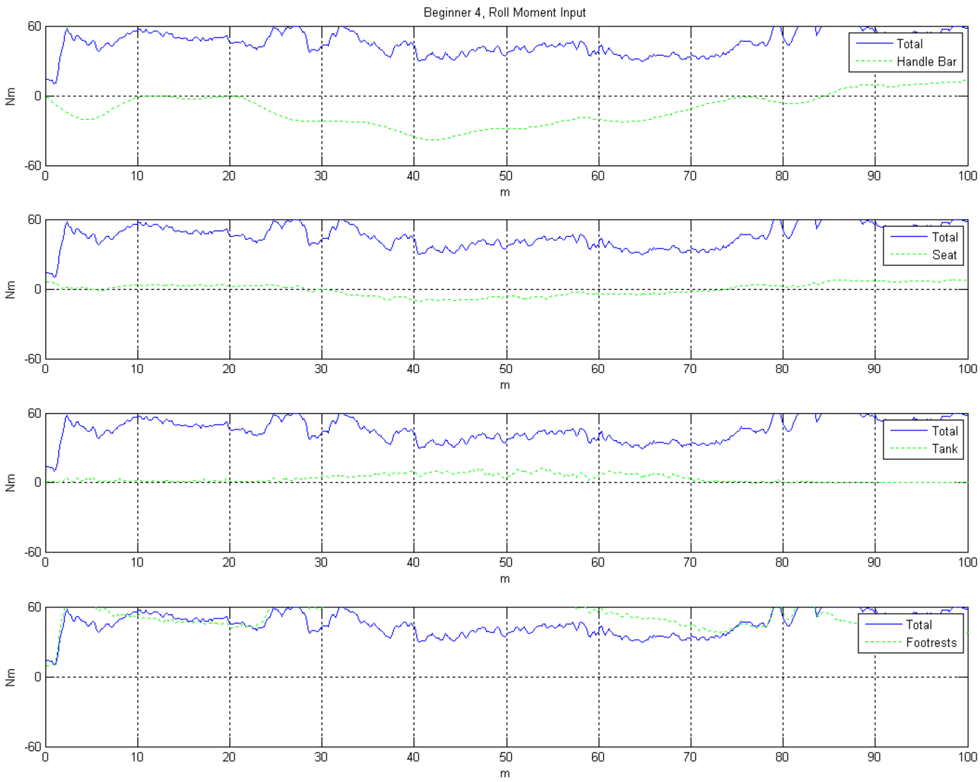

FIGURE 6.23: ROLL MOMENT DISTRIBUTION WITH COMPONENTS, BEGINNER 4

In Figure 6.20 and Figure 6.23 it can already be seen that the moment that the beginner is applying on the handlebar is more vertically directed, with respect to the Test Rider and the Policeman. This is again demonstrated by a cross plot in Figure 6.24. Each marker in the plot represents the combination of the steering torque (X) and the roll moment input (Y) on the steering bar at a particular moment in time.

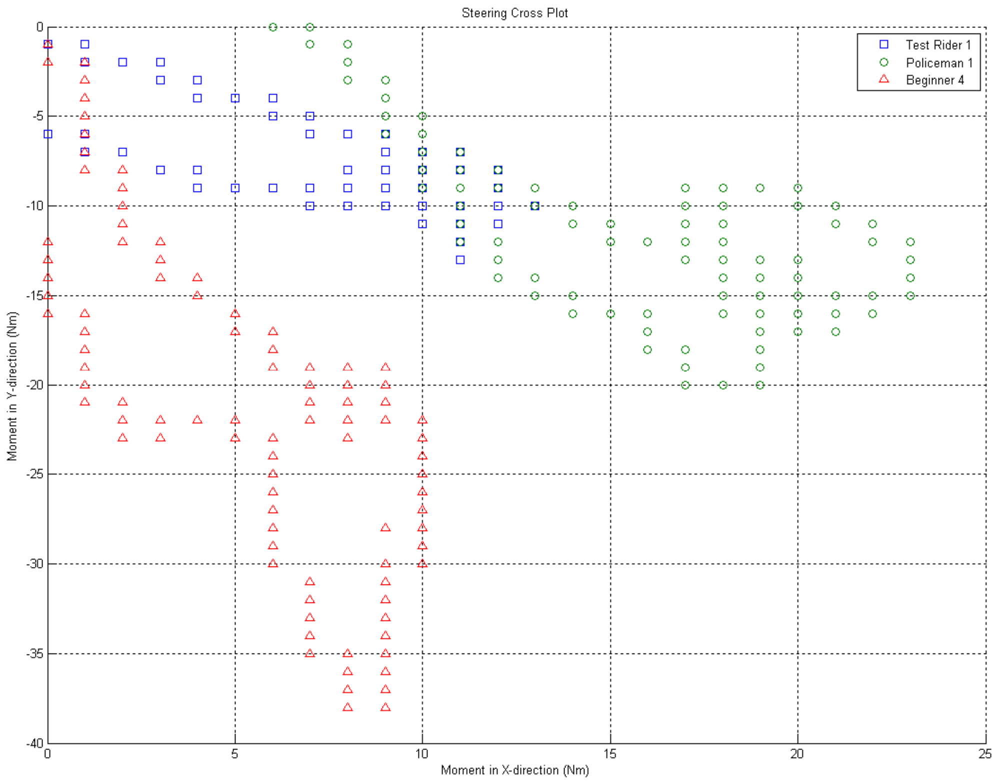

Figure 6.24: Cross Plot of applied Steering Moments in Horizontal (X) and Vertical (Y) direction

The figure also shows that the riding style of the policeman requires a larger steering torque.

Apart from the difference in handling operations, also the ridden paths are different among the riders. Test Rider 1 has a racing past, and racers are known to use the full width of the track. Policemen on the other hand pursue maximum control. This results in different handling characteristics, as has been shown above, but also in a different choice of the intended path. Even in the apex of the corner, they have to be able to avoid any upcoming obstacle. This results in the fact that they always keep some distance to the inner side of the road. This creates a better overview through the corner and it gives the required space to make a pass. For the beginners there is no such trend, but the path is included in the figure, see Figure 6.25.

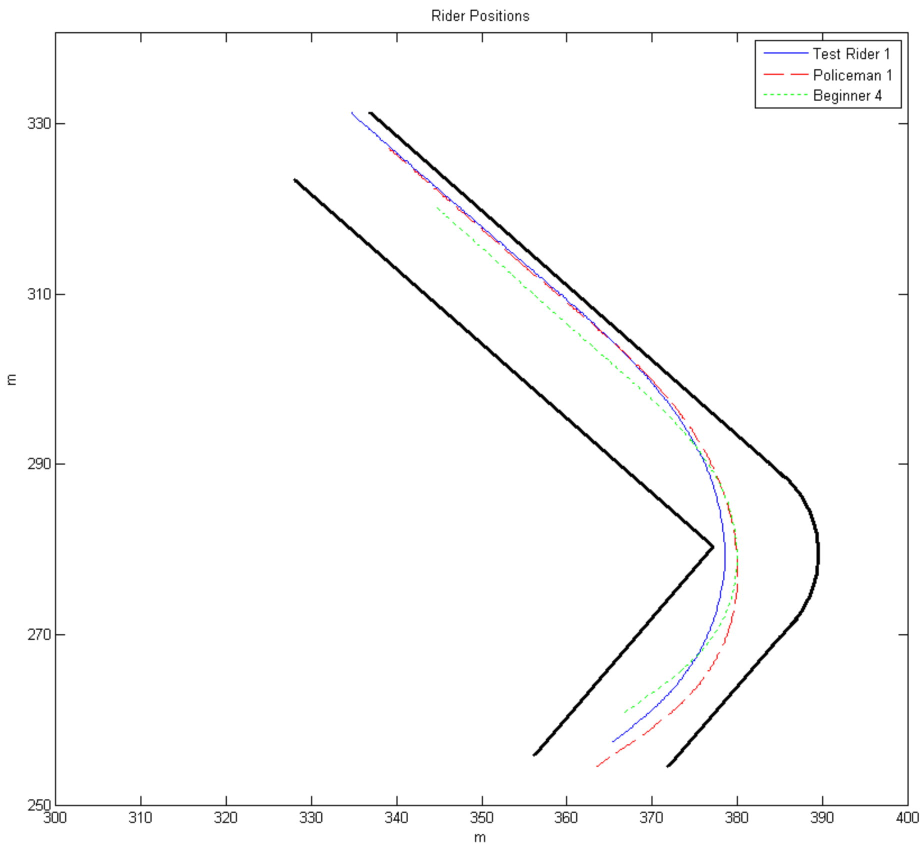

FIGURE 6.25:CHOSEN PATHS, 50 KM/H CORNERING MANOEUVRE

6.2.2.2 HANDLING EFFICIENCY

To quantify the characteristics of the motorcycles handling qualities, J. Koch [3] proposed the following index after experimental tests in “U” turns:

$$Koch\ Index = \frac{\tau_{\delta peak}}{V{\cdot}\dot{\varphi}_{peak}} \left[\frac{N}{rad/s^2}\right] \tag{3.13}$$

In accordance with the indices of the avoidance manoeuvre, also this index has been modified. This gives the following newly introduced equation:

$$Efficiency\ Index = \frac{\tau_{\delta\varphi\ peak}}{V{\cdot}\dot{\psi}_{peak}} \left[\frac{N}{rad/s^2}\right] \tag{3.14}$$

In this section, both indices are referred to. In the next table, the indices for all riders performing the 50 km/h cornering manoeuvre are listed, together with the corresponding parameters, see Table 6.3. V_{min} is in m/s, τ_δ and $\tau_{\delta\varphi}$ in Nm and $\dot{\varphi}$ and $\dot{\psi}$ in rad/s.

TABLE 6.3: INDICES WITH CORRESPONDING PARAMETERS, 50 KM/H CORNERING MANOEUVRE

Rider	V_{min}	τ_δ	$\dot{\varphi}$	KI_φ	$\tau_{\delta\varphi}$	$\dot{\psi}$	EI_ψ
Policeman 1	11.50	23.0	0.49	**4.09**	27.3	0.68	**3.47**
Policeman 2	12.63	16.8	0.55	**2.44**	30.6	0.55	**4.41**
Test Rider 1	10.86	12.7	0.43	**2.70**	17.2	0.63	**2.52**
Test Rider 2	10.17	15.9	0.52	**3.02**	17.1	0.56	**2.99**
Test Rider 3	10.69	15.4	0.49	**2.94**	26.4	0.72	**3.44**
Beginner 1	7.19	9.1	0.21	**5.94**	14.8	0.58	**3.55**
Beginner 2	8.81	16.8	0.30	**6.39**	34.6	0.68	**5.82**
Beginner 3	10.85	21.0	0.58	**3.33**	37.9	0.82	**4.24**
Beginner 4	9.47	10.4	0.29	**3.81**	38.9	0.67	**6.10**

For convenience, the results for both indices are also plotted in a figure by rider category, showing the minimum, maximum and mean value, see Figure 6.26. Having a look at the right figure and at the last column of the table, the test riders are performing relatively well, in particular Test Riders 1 and 2. The beginners are performing less efficient, beginner 2 and 4 in particular.

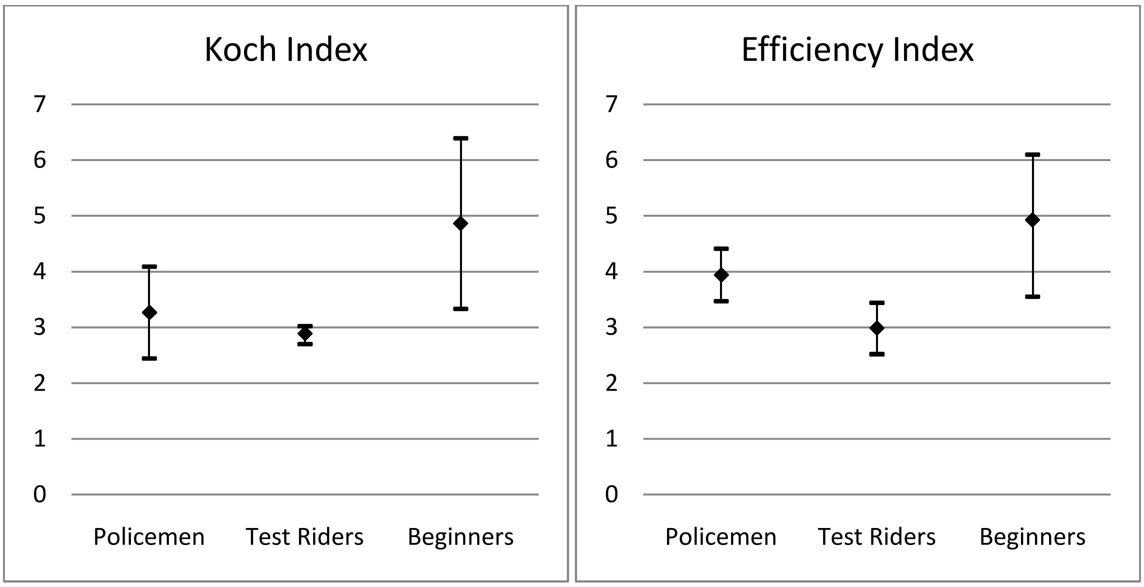

FIGURE 6.26: INDICES, 50 KM/H CORNERING MANOEUVRE

The main cause for this difference is the distribution of the moment on the handlebar. Referring to the third column of Table 6.4 below, it appears that both beginners are putting a lot of force on the handlebar in roll direction with respect to the force in steering direction. In the qualitative comparison of the previous section it has been shown that the motorcycle does not show much response on force input in roll direction. So for the beginners, this way of steering is not the most efficient way.

TABLE 6.4: CHARACTERISTICS OF SELECTED RIDERS

Rider	KI_{φ}	EI_{ψ}	$\tau_{\varphi}/\tau_{\delta}$	M_{φ}
Test Rider 1	2.70	2.52	0.92	-33.6
Test Rider 2	3.02	2.99	0.38	26.9
Beginner 2	6.39	5.82	2.07	92.5
Beginner 4	3.81	6.10	4.22	40.9

That the location of the upper body is influencing the steering torque, becomes clear having a look at the Koch Index of the first column and the roll moment input of the last column of Table 6.4. Test Rider 1 who had his upper body located inside the corner (negative M_{φ}) was steering much more efficient than Beginner 2 who had a positive roll moment input (M_{φ}) outside the corner.

In general the main difference between both indices lies on the input side of the equation. But also on the output side holds that a higher roll rate does not automatically lead to a higher yaw rate. This can be seen in Table 6.3 looking at the data of for example Policeman 2 and Test Rider 1. Despite of a lower roll rate, Test Rider 1 shows a higher yaw rate with respect to Policeman 2.

Comparing the efficiency index with the similar index of the avoidance manoeuvre, the new lane change index, it shows that the differences between the rider categories has increased. The cause for this may lie in the fact that during the cornering manoeuvre the riders were more 'free' to choose their own path and velocity.
The second remarkable fact is that within the beginner category the differences in efficiency have increased. Based on this diversity, it is not justified to put all riders under the same category and demonstrates that there is no stereotype beginner.

6.2.3 MANOEUVRE COMPARISON

The riders were asked to perform the same turn again, but in this case with a higher approach velocity of 80 km/h. The data used in this section is from the same experienced rider as in the previous section. The manoeuvres were performed under the exact same conditions.

Starting from the same type of figure as in the last section, it is easy to observe that the steering goes more aggressively as the graph for the steering torque is much steeper, see Figure 6.27 and Figure 6.28.

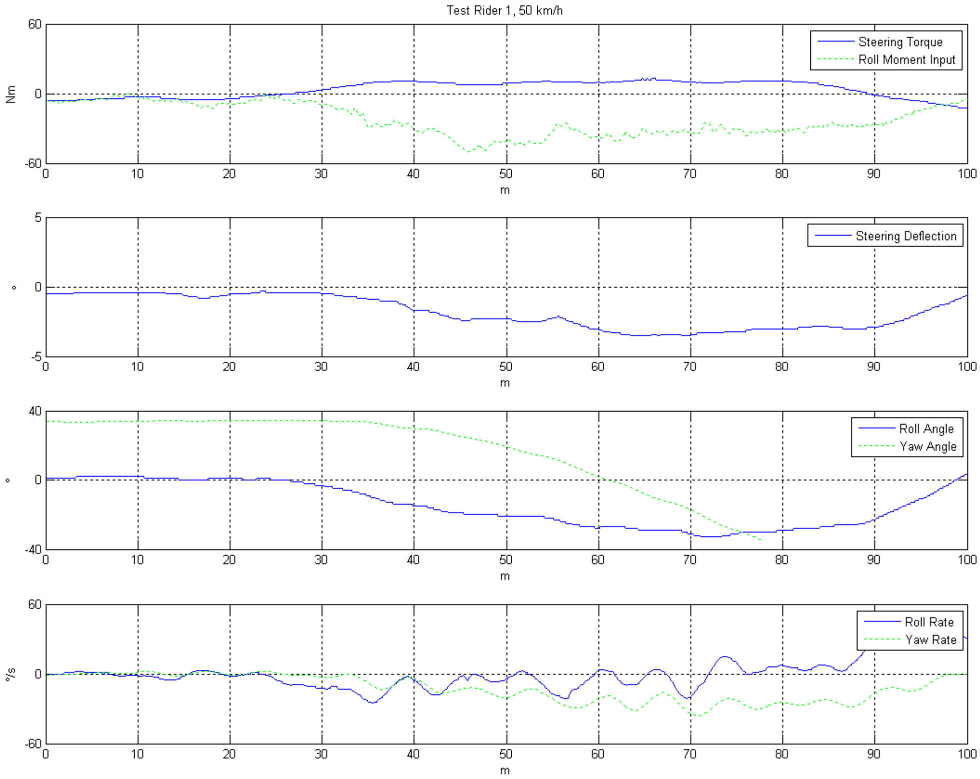

FIGURE 6.27: TEST RIDER 1, CORNERING MANOEUVRE 50 KM/H

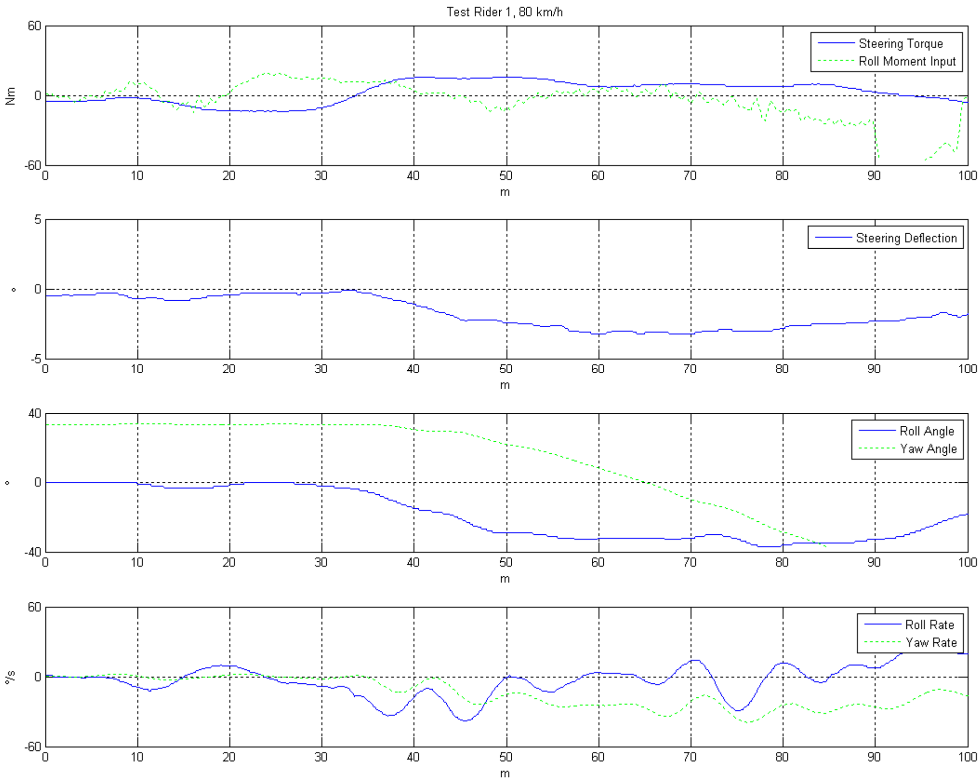

FIGURE 6.28: TEST RIDER 1, CORNERING MANOEUVRE 80 KM/H

Basically, the steering characteristics remain unchanged. The roll and yaw rates become larger and the obtained roll angle is larger. The main thing that is different is the roll moment input. During the 50 km/h turn the upper body was “capsizing” into the corner, at 80 km/h the rider has to move his upper body into the corner actively. This results in a reaction moment outside the corner and can be seen in the figure between ± 18m and ± 40m. Although by sight (on the video) the rider is doing the same with his upper body, the input on the motorcycle becomes different. Half way the turn at around ± 70m, the rider is moving the upper body back to the left to prepare for the upcoming left hand turn. Also this generates a reaction moment.

In the next figures, Figure 6.29 and Figure 6.30, it is shown that the input of the different roll moment components is larger for the 80 km/h turn. This is usually the case for all riders when the mental workload rises.
As soon as a rider thinks he approaches the limits of the grip of the tyres, he becomes more conservative in giving a steering torque and tries to give the motorcycle a direct roll input. This happens when the required approach velocity increases but also under wet track conditions. Also less experienced riders show this characteristic as the manoeuvres are more demanding for this group.

Although the roll moment input is completely different between the manoeuvres but also between the different riders, the principle of steering as it has been explained in section 6.1.1.1, always holds. This indicates that the actual steering is indeed done by applying a steering torque on the handlebar.

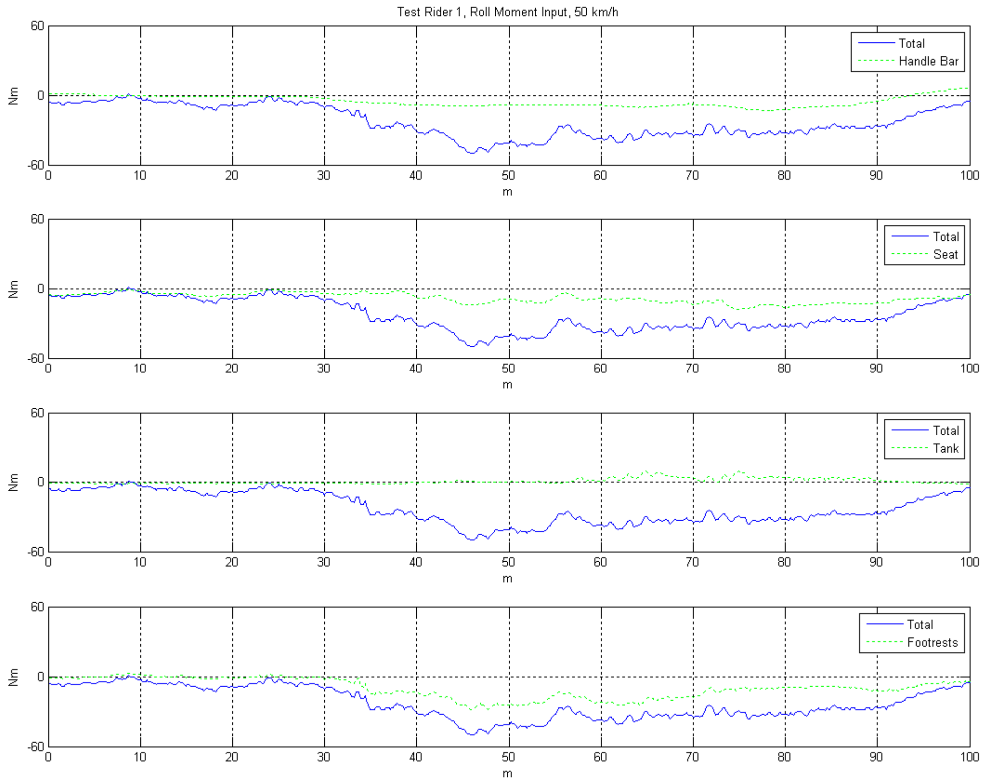

FIGURE 6.29: ROLL MOMENT DISTRIBUTION WITH COMPONENTS, 50 KM/H CORNERING MANOEUVRE

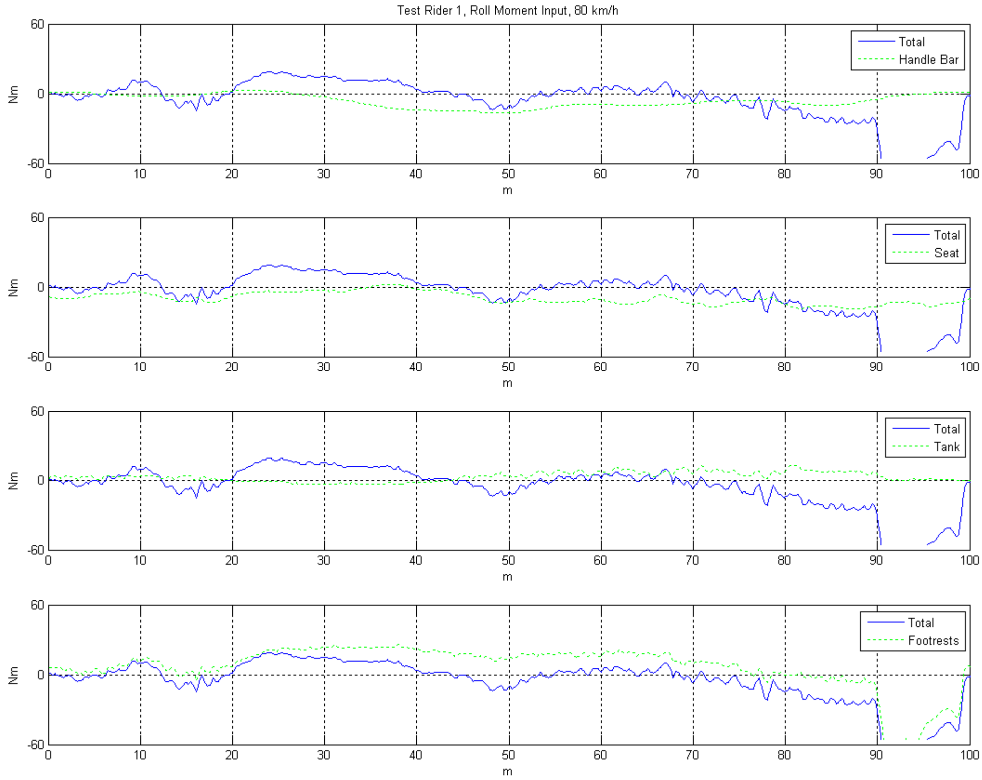

FIGURE 6.30: ROLL MOMENT DISTRIBUTION WITH COMPONENTS, 80 KM/H CORNERING MANOEUVRE

6.2.4 SUMMARY

In this second part of the results, the rider actions and rider/motorcycle response has been described demonstrating a cornering manoeuvre. After that, different riders are compared with respect to their riding style and steering efficiency. Also the influence of velocity is referred to.

The principles of steering as described in the first part also hold for this manoeuvre although it is harder to trace the various characteristics. As this was not a tight and demanding manoeuvre, the motorcycle response was not as clear as during the avoidance manoeuvre.

Comparing the riders it appeared that the main difference lies in the usage of the upper body. The test riders moved their upper body to the inside of the corner, while the policemen move their upper body outside of the corner. The policemen’s way requires a larger steering torque, but results in a more stable steering behaviour.
Beginners are giving a large moment input directly in roll direction, also on the steering bar.

The test riders are most efficient in performing the cornering manoeuvre, the beginners were least efficient. The main cause for this difference is that the test riders are putting relatively more force in steering direction on the handlebar, while beginners put more force in roll direction on the handlebar. It has been shown that the motorcycle does not show much response on force input in roll direction, which makes the steering operation of the beginners inefficient.

Also the inward position of the test rider's upper body reduced the required steering torque. This made Test Rider 1 even more efficient.
The differences in efficiency between the rider categories has increased with respect to the avoidance manoeuvre. Also within the beginner category the diversity increased, which means there is no stereotype beginner.

When the same manoeuvre was performed again with an increased velocity it appeared that the input in roll direction increased. This is usually the case when a manoeuvre becomes more demanding.

A lot of different roll moment distributions have been shown during the rider comparisons and the manoeuvre comparisons, but the principle of steering holds in all cases. This indicates that steering is indeed done by applying a steering torque on the handlebar.

As far as this part of the results is concerned, the tests provided the data and information that we were interested in. A clear understanding of how the riders operate the motorcycle is obtained and mutual comparisons could be made. Naturally, due to the free character of the manoeuvre, the comparisons in efficiency become less significant. The negative influence of this rider freedom on the efficiency comparison is however limited by a proper choice of the parameters in the efficiency indices.

7 Results: Rider Evaluation

During the test day, the riders evaluated their performance according to the performance criteria and their workload, as described in section 5.3 about the test set-up. Directly after finishing the manoeuvres, the riders had to fill in the questionnaire. The outcome of the multiple choice questions results directly in a rating between 1 and 20, in which 20 is the best possible scenario.

7.1 Cornering Manoeuvre

In the next figure, Figure 7.1, the rating is shown divided over the three main rider categories. As discussed in the chapter about the test set-up, the total rating consists of an (semi-)objective and a subjective part. The objective part is directly linked with the performance requirements and the subjective part is based on the workload that the riders experience.

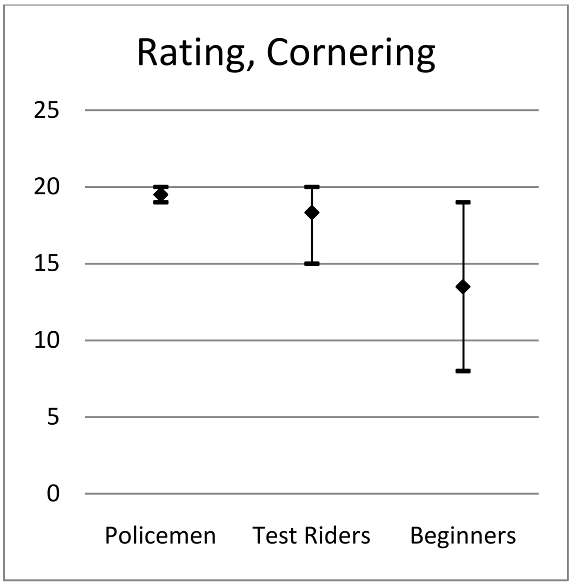

Figure 7.1: Rating, Cornering Manoeuvre 50 km/h

The graph shows similar characteristics as the efficiency indices of the corresponding manoeuvre in section 6.2.2.2 on handling efficiency. The performance of the policemen and the test riders is high and almost the same. Only one test rider just missed the 10 km/h speed requirement, which results in a larger spreading in the rating results. The beginners perform relatively worse and also the spreading in the rating is again large.

In the following table it will be shown how the rating was formed. Note that the first performance criterion about the full control of the motorcycle has been omitted, as all riders fulfilled that requirement.

TABLE 7.1: RATING FORMATION, CORNERING MANOEUVRE

Rider	Performance Criteria		workload	Physical		Mental		Rating
	± 20 km/h	*± 10 km/h*		*Steering*	*Body*	*Attention*	*Stress*	
Policeman 1	V	V	**4**	4	4	3	4	**19**
Policeman 2	V	V	**5**	5	5	5	5	**20**
Test Rider 1	V	V	**5**	5	5	5	5	**20**
Test Rider 2	V	-	**5**	4	4	4	5	**15**
Test Rider 3	V	V	**5**	5	5	5	5	**20**
Beginner 1	-	-	**3**	3	4	4	4	**8**
Beginner 2	V	-	**3**	2	2	3	2	**13**
Beginner 3	V	V	**4**	5	4	3	5	**19**
Beginner 4	V	-	**4**	4	5	3	4	**14**

V=pass, -=fail, 1= Intolerable, 2= Extensive, 3=Considerable, 4=Moderate, 5=Low

From the columns about the performance criteria, it follows directly that the beginners remain behind. Beginners 2 and 4 fail to meet the second velocity criterion. Beginner 3 is a positive exception, while beginner 1 also fails to meet the first velocity requirement.
Not only the performance of the beginners is lower, their perceived workload is also higher with respect to the policemen and the test riders. For most of the beginners, the manoeuvre requires considerable attention.
Beginner 2 indicates the physical workload as extensive, which corresponds well with the efficiency characteristics in section 6.2.2.2., showing a high moment input on the steering bar. On the other hand, Beginner 4 indicates the mental workload as main contributor to the workload, while the data also showed a high moment input on the steering bar for this rider. Beginner 1 indicates the steering as considerable workload, while the data shows that this rider used the lowest amount of input moment on the steering bar with respect to all the other riders.

Although the rider's opinion has to be respected, the self evaluation does not stroke very well with the data. This indicates that this manoeuvre was not sufficiently prepared for a good evaluation. The main reason for this is the rider's frame of reference. The riders have a different background. The policemen and the test riders are used to extreme conditions and from that point of view the workload during this manoeuvre was low. For the beginners the opposite holds.

It would have been better to start from a common reference point. Starting from a certain configuration and then slightly change some conditions would make it possible for the riders to experience a "difference" which is better to describe than just a single experience. The change in conditions can be obtained by changing any motorcycle settings or by changing manoeuvre parameters.
As the bike's settings are fixed only the manoeuvre parameters can be changed. As the track was fixed too, the best way to change the conditions was to slightly increase the velocity. The rider then can indicate the changes he is experiencing and how the new condition influences his workload with

respect to the previous case. Also when the rider fails to complete the manoeuvre according to the performance requirements, he can indicate what exactly limits his performance.
It is important that the other manoeuvre parameters remain constant. This means also that the liberty of the rider to chose his path should be restricted.

The corner was part of a track that had to be completed three times before the rider had to evaluate his performance. This complete track required too much attention and there was too much time between the actual manoeuvre and the evaluation.
This does not mean that the manoeuvre was useless. A lot of valuable data is obtained on how a rider is operating the motorcycle and about the differences between various types of riders. To obtain data on the natural riding style, the riders had a lot of freedom. Unfortunately this is conflicting with the recommendation given above and consequently there was no sufficient base for a good evaluation.

7.2 Avoidance Manoeuvre

In accordance with the cornering manoeuvre, the riders had to evaluate their performance for the avoidance manoeuvre. This manoeuvre was performed three times with three different velocities, 50, 80 and 120 km/h. Due to time restrictions, all three cases were performed in one session and only one evaluation form had to be completed. The riders were encouraged to give commend about the differences they experienced. This gave the results as in Figure 7.2.

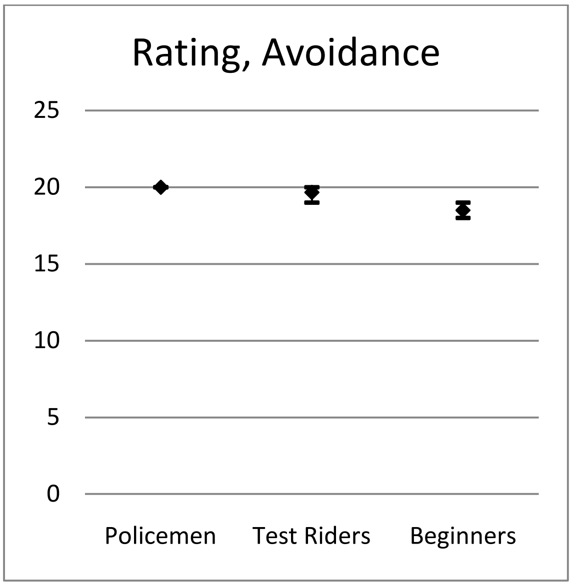

Figure 7.2: Rating, Avoidance Manoeuvre

This time the differences are marginal. All the riders met the performance criteria. The only differences lie in the riders perception of the workload. In the following table it will be shown how the rating was formed.

TABLE 7.2: RATING FORMATION, AVOIDANCE MANOEUVRE

Rider	Performance Criteria		Workload	Physical		Mental		Rating
	2A	*2B*		*Steering*	*Body*	*Attention*	*Stress*	
Policeman 1	V	V	**5**	5	5	5	5	**20**
Policeman 2	V	V	**5**	5	5	5	5	**20**
Test Rider 1	V	V	**5**	5	5	5	5	**20**
Test Rider 2	V	V	**4**	4	4	4	4	**19**
Test Rider 3	V	V	**5**	5	5	5	5	**20**
Beginner 1	V	V	**3**	5	2	2	3	**18**
Beginner 2	V	V	**4**	4	4	3	4	**19**
Beginner 3	V	V	**4**	5	4	3	5	**19**
Beginner 4	V	V	**3**	3	5	4	4	**18**

1= Intolerable, 2= Extensive, 3=Considerable, 4=Moderate, 5=Low

The beginners indicated that mainly the required attention causes a higher workload. The riders had to concentrate on the signal, the object and their velocity. It is reasonable that it is more demanding for beginners.
Beginner 1 experienced the use of the body as extensive, but this is not traceable in the data with respect to the other riders.
From the data it followed that the steering moment increased with increasing velocity, but none of the riders commented on that.

Also this evaluation is not satisfactory. The cause for this is basically the same as for the cornering manoeuvre. On top of that, maybe it was too much asked from the riders to assess their workload while they also had to concentrate on the signal, the object and their velocity.

The marginal difference in performance is actually indicative for a test which performance criteria are too light. For this manoeuvre, tighter performance criteria would influence the safety. For that reason there has been opted for criteria within anyone's capabilities.

8 DISCUSSION

The first purpose of the test was to get an accurate view on the principles of steering a motorcycle. Therefore, manoeuvres were developed to obtain proper data. All rider actions were monitored, as well as the motorcycle response. The monitored rider actions were not limited to steering actions only, also usage of the body resulting in forces on the motorcycle was measured. To encourage the natural riding style of all the riders, the riders were free to choose their own path.

A total of nine riders participated, divided beforehand over three categories: Policemen, Test Riders and Beginners. This provided the possibility to compare the different categories to see if there are indeed differences in riding style. This is the second purpose of the test.

The third purpose of the test was to verify how the riders experienced the manoeuvres and to try to relate their experiences and perceived workload with the data.

In this section, an extract will be given of the results. It concludes with a discussion whether the desired purposes are achieved.

8.1 STEERING

When a rider is entering a turn, he initiates a counter steering torque. This results in a steering deflection in opposite direction with respect to the intended heading. Consequently, the motorcycle starts to yaw, again in opposite direction. Due to this yawing characteristic, the centrifugal force forces the motorcycle to roll. As soon as the motorcycle is rolling, the steering deflection as well as the yawing velocity changes direction. From this moment on, the roll motion, the steering deflection and the yawing motion are all in the direction of the intended heading. Throughout the turn, the steering torque always remains in counter direction. Initially it initiates the turn, later it prevents the steering bar from rotating further. During a lane change manoeuvre it appeared that the majority of the steering torque is used to counteract the gyroscopic moment resulting from the roll rate in combination with the spinning of the front wheel.
The other gyroscopic moment originating from the velocity of the steering deflection in combination with the rotational velocity is rather small. The assistance that this moment provides during corner entry is negligible.

The rider can influence the amount of steering torque with lateral motion of the upper body center of mass. The steering torques becomes smaller when the center of gravity is located inside the corner and larger when it is located outside the corner with respect to the motorcycle plane of symmetry. It appeared that the usage of the upper body was very diverse among the riders and during the different manoeuvres. Apart from the influence on the steering torque, this diversity in roll moment input hardly had its influence on the motorcycle response. The principle of steering as demonstrated above however holds for all riders during all manoeuvres. This means that steering a motorcycle is indeed done by applying a steering torque and not by using the upper body to give an input directly in roll direction.

When the mental workload increases, for instance by raising the velocity as in section 6.1.3 or in rainy conditions (has been tested but is not part of this report), riders have the tendency to apply more force directly in roll direction. They become more conservative in applying the steering torque.

8.2 Rider Comparison

The riders are compared based on the handling characteristics following from the data plots. The riders are also compared regarding efficiency.
From the three categories, Policemen are known to have a deviating riding style. They pursue maximum control at all times and they need to have a good survey. They learn to push the motorcycle down in a corner while maintaining their upper body upright. This is confirmed by the data. Their upper body center of gravity is located outside the corner and this consequently results in a higher steering torque.
Test Riders have a racing background which usually means that they hang into the corner. This results in a lower steering torque, according to the same principle as for the policemen.
As far as the beginner category is concerned, there is no specific feature beforehand about their riding style. Looking at the data some do apply a lot of force directly in roll direction, which is highly ineffective. Overall their riding style is divers.

Regarding efficiency, the results were that the test riders are most efficient, followed by the policemen. The beginners performed relatively worse and also the spreading of the results is relatively large. The first condition for an efficient performance is that the force on the handlebar has to be applied in steering direction, and not in roll direction. As mentioned above, beginners apply a lot of force in roll direction and that makes their handling inefficient. The second condition for an efficient performance is to position the upper body center of gravity into the corner. This makes the test riders more efficient. The policemen had their upper body center of gravity located outside of the corner, which made them less efficient with respect to the test riders. However, this way of steering provides better control and in particular at low speed corners or corners with low corner radii, this is the recommended way.

To obtain the steering efficiency, an Efficiency Index is deduced from an existing index (Koch Index) relating the rider input with the motorcycle output. It provided a fair comparison on efficiency, that corresponded very well with the overall perspective that followed from the data.

8.3 Rider Evaluation

After performing the test, the riders had to rate their performance according to manoeuvre related performance criteria. Apart from rating the performance they also had to rate their perceived workload.

During the cornering manoeuvre, the performance of the beginners remain behind. And in correspondence with the efficiency index there was a large spreading in results. This means that there is no stereotype beginner. During the avoidance manoeuvre, the difference in performance between all riders was modest. Most beginners consider the mental workload as the mean factor influencing their performance, as the manoeuvre required considerable attention.

Although the riders opinion has to be respected, the perceived workload of all the riders did not stroke with the data. The reason for this is the difference in experience and background. Policemen and test riders are used to extreme riding conditions and from that point of view their workload is low. For the beginners, the opposite holds while all riders may experience the same amount of workload.
Starting from a common frame of reference and then slightly change a manoeuvre parameter, would make the rider experience a "difference". According to this difference the rider might be able to describe what he feels with respect to the previous situation and how that influences his performance.
Most of the riders failed to give comment on their workload which indicates that the manoeuvres required too much attention.

8.4 Overall

As described in the first lines of this section, the test had three main purposes. The first purpose was to gain insight on the principles of steering a motorcycle. From the avoidance manoeuvre, the steering characteristics as described in section 8.1 have been deduced. Due to the aggression (enhanced by the surprise effect) with which the manoeuvre was performed the data provided a clear understanding.

The second purpose was to identify differences in the natural riding style. The cornering manoeuvre with its free character showed the (lack of) differences between the different rider categories as demonstrated in section 8.2. Both manoeuvres provided the possibility to compare the riders according efficiency, although the free character of the cornering manoeuvre, at which the riders were riding different lines, made the comparison less significant.

The third purpose of the test was to verify how the riders experienced the manoeuvres and to try to relate their experience with the data. The riders were hardly able to comment about their experience. Unfortunately it was impossible to relate the rating with the data, due to the absence of a common frame of reference. It would have been better to describe a more tight manoeuvre and to change the conditions in small steps, as described in section 8.3.
Optimizing the manoeuvre to meet the third purpose would conflict with the fact that the riders all had to ride in their own natural way.

In the end, the test went very well and has been very useful. Despite of the strong wind, the track was perfect for the manoeuvres and above all, it was save.
The wind did influence the roll and yaw rate. For that reason only for the 50 km/h manoeuvres the efficiency is determined and compared.
The motorcycle has been prepared more than sufficiently. Only the front wheel speed sensor failed on a few occasions, but there was a second speed sensor at the rear wheel so this did not cause any problems. The newly introduced laser distance sensors have proved to provide an easy but solid way to determine the roll angle. Also the mounted camera's provided the extra information that was required to distinguish rider actions from motorcycle/rider reactions.

9 Conclusions and Recommendations

Steering is done by applying a steering torque on the steering bar. A rider initiates a counter steering torque in opposite direction with respect to the intended heading. This causes a steering deflection and consequently a yawing motion in the same direction. The centrifugal force makes the motorcycle roll to the other site, the intended heading. Once the motorcycle starts to roll, also the steering deflection and yawing motion changes sign to the intended heading. The rider remains applying a counter steering torque throughout the complete turn.

Steering is not done using the upper body. The position or motion of the upper body does however influence the steering torque. When the mental workload rises, riders have the tendency to use the upper body more.

The gyroscopic moment originating from the velocity of the steering deflection in combination with the spinning of the front wheel is very small. The ‘help’ that this effect would provide according to [4] is negligible. During manoeuvres with a high roll rate, the gyroscopic moment originating from the roll rate in combination with the spinning of the front wheel requires the majority of the applied steering torque.

Test riders were most efficient in their steering actions. They apply a relatively large amount of force on the handle bar in steering direction and have their upper body located into the corner when performing a turn. Policemen are less efficient with respect to the test riders as they have their upper body located outside the corner. Beginners were inefficient. They applied a large amount of force directly in roll direction.
The policemen’s way of steering is more stable and is recommended particularly at low speed manoeuvres, despite of the fact that it requires more steering torque input.
The newly introduced efficiency indices proved to correspond well with the overall impression of the data and are in this investigation definitely preferable to the existing Koch Index.

There is no stereotype beginner. Within the beginner category, the results about handling characteristics and efficiency were very divers. Beginners consider the mental workload as main factor that limits their performance.

The way of testing provided a lot of useful data but unfortunately it was not suited for a decent self evaluation for the riders. An adequate test manoeuvre should have a stepwise increase in difficulty which would provide the possibility for the riders to relate their feelings with respect to the previous situation. This also requires a tighter definition of the manoeuvre. During our test, the lack of a frame of reference made the evaluation weak.
The cornering manoeuvre was part of a track that had to be completed. This made it hard for the rider to remember the characteristics of that particular corner.

Optimizing the manoeuvre for the self evaluation would conflict with the purpose to identify differences in riding styles, so unfortunately it was impossible to create a win-win situation.

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