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Objective Methods for the Assessment of Passenger Car Steering Quality

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Abstract

Steering feel and quality are terms commonly used in the automotive industry when describing passenger car steering systems. However, a procedure for the quantification of these terms does not exist, let alone a concise definition of what they constitute.

This thesis puts forward a hypothesis by which steering quality and feel are described by the input/output relationships of the steering system and how they are perceived by the driver. Good control properties are postulated for these relationships and an experiment is conducted, where they are altered in a manner proposed to affect quality. A methodology for the objective assessment of the control properties is developed, employing vehicle dynamic testing and representation by a mathematical model. This is put into practice to evaluate the outcome of the experiment.

It was found that the methodology was successful in detecting and quantifying the alteration in the vehicle control properties. A subjective evaluation was performed to assess the experiment in terms of the quality and feel perceived by the driver. The subjective judgement delivered a result, where the deviation in quality agreed with the objective quantities hypothesised to describe quality.

The thesis provides a significant step in the understanding of what is termed steering feel and quality. The methodology, successful in quantifying the experimental results with respect to quality, constitutes a scientific advancement in the current procedures for the assessment of steering quality.

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List of Symbols

Symbol		*Description*	*Unit*
a_y	:	Lateral acceleration of vehicle	ms^{-2}
C_F	:	Effective front axle cornering stiffness	N/Rad
C_R	:	Effective rear axle cornering stiffness	N/Rad
c_S	:	Steering Column Stiffness	N/Rad
C_H	:	Hardy disc stiffness	N/Rad
C_T	:	Torsion bar stiffness	N/Rad
d_S	:	Steering column damping	Nms/Rad
d_Z	:	Steering rack Damping	Nms/Rad
F_C	:	Coulomb Friction	N
F_{Fr}	:	Friction force on steering rack	N
F_W	:	Side wind force	N
F_x	:	Tyre longitudinal force	N
F_y	:	Tyre lateral force	N
H_{cc}	:	Power steering valve characteristic curve	
g	:	Gravitational acceleration	ms^{-2}
i	:	Steering ratio	
i_D	:	Dahl friction modulation parameter	
I_z	:	Vehicle yaw moment of inertia	$kg\,m^2$
I_H	:	Steering (hand) wheel moment of inertia	$kg\,m^2$
I_F	:	Front axle steer moment of inertia	$kg\,m^2$
l	:	Length of vehicle wheelbase	m
l_F	:	Distance of front axle to CG	m
l_R	:	Distance of rear axle to CG	m
m	:	Vehicle complete mass	kg
m_F	:	Mass of front wheel/steering rack body in steering model	kg
M_{Fr}	:	Friction moment on steering column	Nm
M_H	:	Moment at the steering wheel (hand wheel)	Nm
M_z	:	Tyre aligning moment	Nm
n_c	:	Mechanical trail	m
n_p	:	Tyre pneumatic trail	m

Symbol		*Description*	*Unit*
n_r	:	Steering pinion radius	m
n_s	:	Length of steering linkage lever arm	m
t	:	Time	s
v_x	:	Vehicle longitudinal velocity	m/s
v_y	:	Vehicle lateral velocity	m/s

Greek Symbol		*Description*	*Unit*
α	:	Tyre slip angle	deg
β	:	Vehicle slip angle	deg
δ_F	:	Front axle steer angle	deg
δ_H	:	Steering wheel angle	deg
δ_{Hi}	:	Input steering wheel angle	deg
δ_{Ho}	:	Output steering wheel angle	deg
δ_P	:	Free play in steering column	deg
ε_{CG}	:	Distance of aerodynamic lateral COP to CG	m
γ	:	Caster Angle	deg
ρ	:	Radius of curvature of vehicle path	m
σ	:	Dahl Friction coefficient of rest stiffness	
ψ	:	Vehicle yaw angle	deg

Abbreviation		*Description*
CG	:	Vehicle centre of gravity
CR	:	Vehicle centre of rotation
COP	:	Vehicle aerodynamic centre of pressure
ECU	:	Electronic Control Unit
ISO	:	The International Organization for Standardization

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Chapter 1

Introduction

1.1 Objectives of the Work

This work aims to bring more clarity and scientific analysis to the area of passenger car steering system quality. The ultimate objective is to provide a method for the testing and simulation of steering feel and quality. It will thus provide a tool for its analysis and quantification, which may then be used in the design phase of vehicle engineering.

An insight into basic properties of a steering system is provided and their effects on the quality of that system can be quantified. This is achieved through the formulation of a hypothesis on what represents the quality of a steering system and then the use of objective testing and simulation to test it. The investigation is reinforced by subjective evaluation.

1.2 Background of Testing and Simulation in the Automotive Industry

It is currently common knowledge in the industry that objective measurement and simulation are essential tools in vehicle development [Rönitz, Braess & Zomotor 1977, Braess 1982, Zomotor, Braess & Rönitz 1997, Zomotor 1998]. In addition to reducing development times, they serve as invaluable tools in specific problem solving and the general understanding of the engineering principles, which we put into practice. An indication of how important objective testing has become is the increasing number of international standards in the area of vehicle dynamics and handling assessment [Zomotor et al. 1997, Zomotor 1998].

Although objective testing is used in modern vehicle development, subjective evaluation using trained test drivers still plays a large and necessary role, [Crolla, Chen, Whitehead & Alstead 1998]. However, it is often the case that the subjective and objective aspects of development are carried out without sufficient integration and thus, there remains room for improvement for their combined usage in the development process. Sharp [2000], Neukum & Krüger [2001] and Neukum, Krüger & Schuller [2001] point out shortcomings or problems in the existing current practices with regard to the usage of subjective and objective correlation. White [1993], and Sharp [1999] both suggest that an alternative approach must be taken with respect to the judgement of quality. This is a principle with which the author agrees. Therefore, this thesis does not use a conventional approach, where a number of manœuvres are both objectively and subjectively evaluated and a statistical analysis is performed to extract some correlations as in [Bergman 1973, Crolla et al. 1998, Chen 1997]. This method can yield useful correlations. However, it does not necessarily result in a better understanding of the system under scrutiny.

This thesis is hypothesis driven and includes a mathematical simulation of the experiment. This is an attempt to gain a real understanding of the system behaviour.

1.3 Basics of Steering

1.3.1 The Steering System

The schematic in figure 1.1 and the photograph in figure 1.2 show the basic components of a power assisted rack and pinion steering system. The numbers in parentheses in the following paragraphs refer to to the numbered labels in the figures. The hand wheel (6) is attached to the steering column (1), which contains an elastic damping element called a Hardy disc (7), whose purpose is to isolate the controller from unwanted disturbances. The column is then attached to the rack and pinion steering gear (2). The ends of the rack are linked to the track rods (5), which are connected to the road wheels, via the steering arms.

The Rack and Pinion Power Steering Gear

The rack and pinion power steering gear used in this study comprises a mechanical steering gear, a steering valve and an integrated power cylinder as depicted in figure 1.3.

The rack housing (1) contains the rack (2) and integrated piston (3). The pinion's (4) teeth mesh with the rack teeth and translate the rotation of the steering column into an axial translation of the rack. This is transferred to the road wheels via the track rods (8) (See also (5) figure 1.1), which are attached to the ends of the rack. To reduce play between the rack and pinion, the rack is pressed against the pinion by a

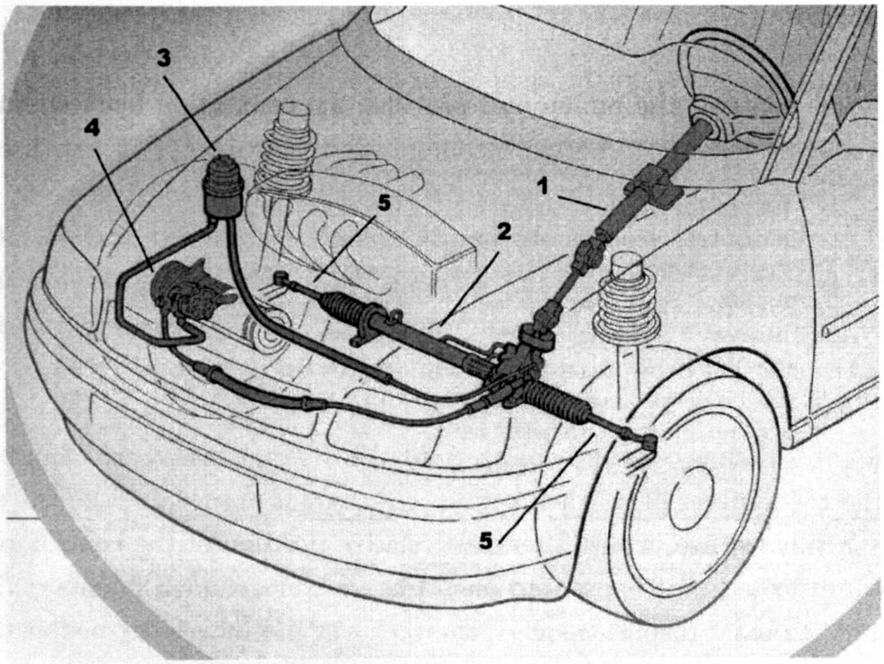

Figure 1.1: Schematic of Steering System in vehicle [ZF Lenksysteme GmbH 2000]

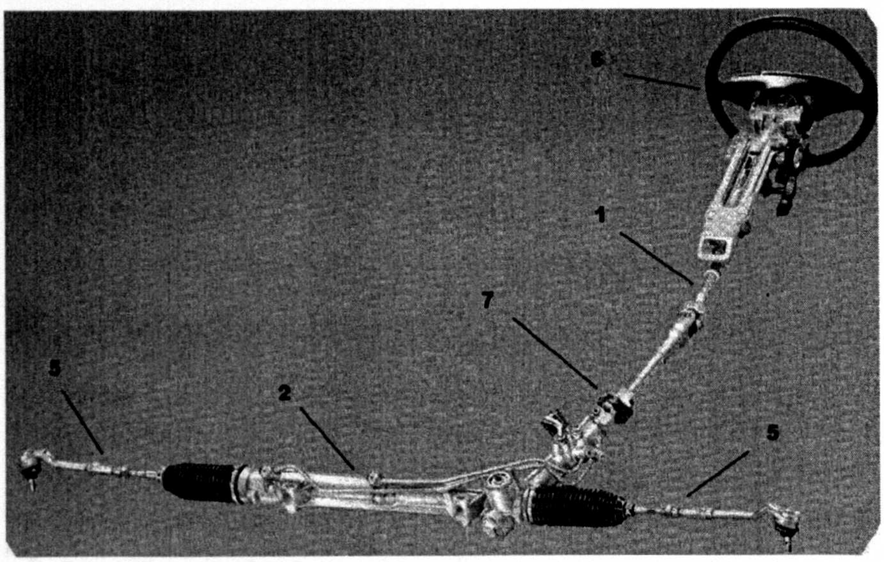

Figure 1.2: Photograph of Steering System [ZF Lenksysteme GmbH 2001]

1	*Steering column*	2	*Rack and pinion steering gear*
3	*Oil reservoir*	4	*Steering pump*
5	*Track rod*	6	*Steering wheel*
7	*Hardy disc*		

Table 1.1: Legend for figures 1.1 and 1.2

spring loaded yoke.

The rotary valve contains the pinion and provides the connection between the pinion and the steering column. The valve comprises the valve rotor (5), with control grooves on its surface area, and the valve sleeve (7). This has axial grooves, which are matched to the control grooves on the rotor. The sleeve and rotor are attached by means of a torsion bar (6). The rotor is connected to the steering column and the sleeve to the pinion. This means that the torsion bar provides a direct mechanical linkage from the steering column to the pinion.

A torque in the steering column coming from the steering wheel will cause a deflection in the torsion bar. This then causes a change of position of the valve rotor relative to the valve sleeve, which alters the relative position of the control grooves. This allows pressurised oil to pass into one of the power cylinder chambers (ZL) or (ZR) assisting the axial displacement of the rack via the integrated piston (3) and thus delivering power assistance [ZF Lenksysteme GmbH 2000].

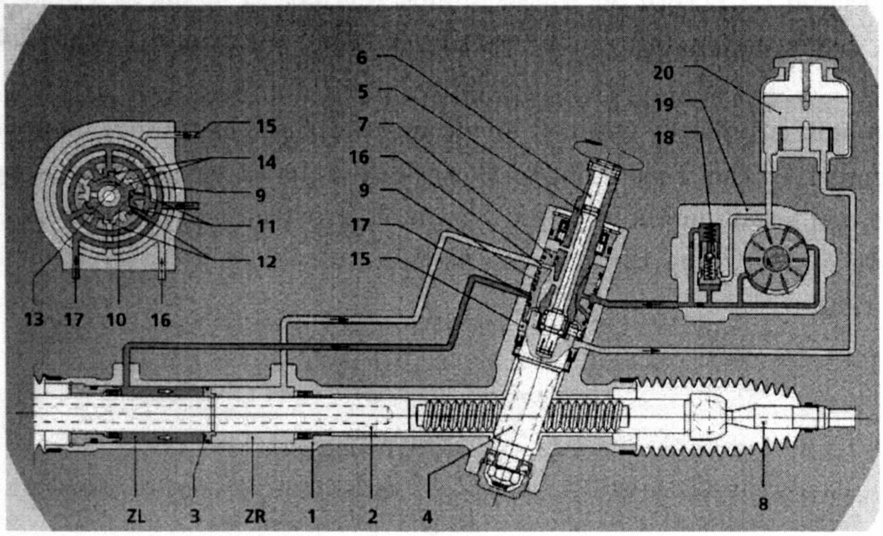

Figure 1.3: Rack and Pinion Steering Gear [ZF Lenksysteme GmbH 2000]

1	*Housing*	2	*Rack*
3	*Piston*	4	*Pinion*
5	*Valve rotor*	6	*Torsion bar*
7	*Valve sleeve*	8	*Track rod*
9	*Feed oil radial groove*	10	*Feed oil control groove*
11	*Feed oil control edge*	12	*Axial groove*
13	*Return oil control groove*	14	*Return oil control edge*
15	*Return oil chamber*	16	*Radial Groove*
17	*Radial Groove*	18	*Pressure relief and flow limiting valve*
19	*Steering pump*	20	*Oil Reservoir*
ZL	*Power cylinder, left*	ZR	*Power cylinder right*

Table 1.2: Legend for figure 1.3

1.3.2 The Kingpin Axis and Mechanical Trail

The kingpin axis is defined as the axis around which a front wheel is steered. The track rods (Section 1.3.1) turn the wheels around this axis by acting at a point on the wheel hub a distance away termed the steering linkage lever arm, n_s, figure 1.4.

The kingpin axis is typically inclined at an angle in the longitudinal plane, as depicted in figure 1.4. The angle of inclination is called the caster angle, γ. A positive caster angle will result in the kingpin axis intersecting ground level ahead of the centre of tyre contact. This distance can be called caster trail, constructive trail or mechanical trail, n_c.

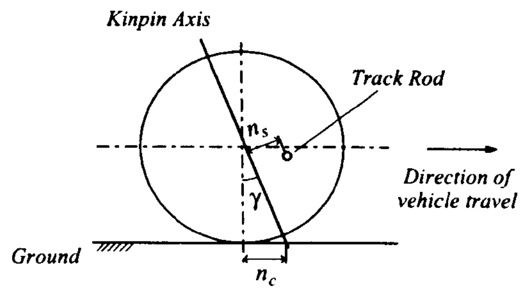

Figure 1.4: The Kingpin axis

1.3.3 Forces at the Tyre Relevant to Steering

While cornering, the tyres generate lateral forces. It is these forces which enable the car to turn. The forces act on the contact patch, i.e. the area where the tyre is in contact with the road surface. The tyre then drifts to the side and the angle made between the direction of travel of the tyre and the direction of travel of the vehicle is called the slip angle. The profile of the lateral forces acting at the contact patch takes a form similar to that in figure 1.5, which has its centroid towards the rear of the contact patch behind the centre of the tyre. This force is conventionally represented by a force, F_y, and a moment, M_z, acting at the centre of the tyre contact (figure 1.6). The lever arm of this force about the centre of tyre contact is called pneumatic trail, n_p (figure 1.5).

As the slip angle increases, the profile of the lateral forces changes shape, with the centroid moving forward and thus reducing the pneumatic trail. The lateral forces also diminish as the slip angle increases and the behaviour approaches that of a locked wheel [Gillespie 1992].

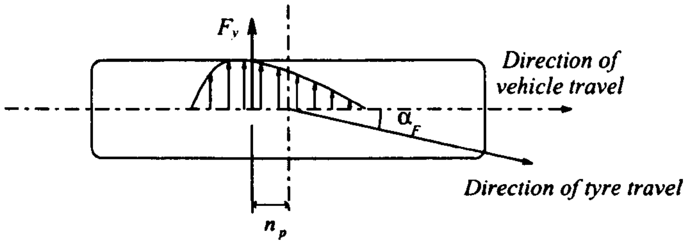

Figure 1.5: Lateral force profile acting on the tyre.

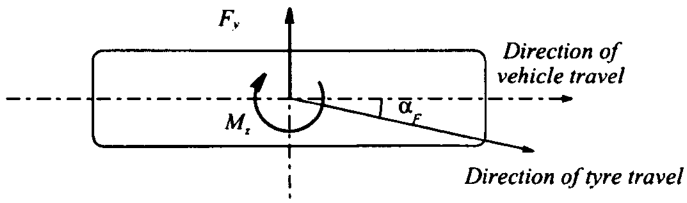

Figure 1.6: Resultant force and moment acting at tyre centre.

1.4 Steering Feel and Quality

Reynolds [1998] describes steering feel as one of the automobile's most elusive and abstract properties. He emphasises its importance when saying: 'Of all the things I want to know about cars, understanding steering feel is very near the top of the list'. This comment is representative of many individuals, as steering feel is a term used copiously in connection with the evaluation of passenger cars by the industry, press and the public. Almost everyone involved with or enthused by the automobile will have an opinion on what steering feel constitutes and what represents 'good' steering feel.

The word feel can mean to touch, perceive, sense, or experience emotion. Since it applies to every thing of every type perceived or sensed, with people being extremely receptive, it is impossible to measure, quantify or separate into categories. Thus, one cannot judge or criticise what a human describes as feel. However, there is some agreement on what is termed 'steering feel' in the automotive press and the industry. The term is being used more frequently as the quality of automobiles improves. As modern day cars increase in performance, functionality and refinement, it is becoming increasingly difficult to differentiate between them. The sole method of differentiation can often be either a purely subjective opinion or a particular quality that cannot be accurately described using existing terminology. It is this which, in the context of handling or steering, can be frequently described as steering feel. The usage of the term on its own, without reference to another aspect of quality or more description, is largely useless. It is when the term is used in conjunction with a description of some more qualitative aspect, that it is evident what the subject in fact is referring to.

In the automotive press, the word feel is associated with terms such as 'direct', 'talkative', 'informative', 'grip', 'feedback', 'steering effort', 'stability' and 'security'. This connects steering feel to qualitative terms and provides the writers with a terminology to describe quality. Steering feel is thus used as a term to describe steering quality along with the ideas of information, communication and security. The following comments are used in positive appraisals of the vehicle's handling and steering: 'a wealth of information about grip', 'paints a detailed picture', 'sends messages', 'connects the driver directly to the road', 'communicates'.

Steering feel is, by definition, subjective. To 'feel' requires a subject. Therefore, trying to define it in scientific or objective terms may seem a paradoxical exercise. However, since it is a term extensively used in automotive development as a measure quantifying vehicle quality, it must be understood if we are to move forward in this imprecise area. Steering feel is about the coupling between driver and vehicle, man and machine. How the driver communicates his input to the vehicle and how the vehicle communicates its output to the driver. The definition is formulated as follows:

Firstly, the driver is acting as vehicle controller. He gives a control input into the system and expects a particular response. This input-response relationship is then interpreted by the subject as how the car feels.

Secondly, the driver is susceptible to feedback from the car. Certain forces and signals suffered by the controller in the automobile are perceived as the vehicle's feedback to the driver, especially torques transmitted through the steering wheel. This feedback, particularly the part thereof transmitted through the hands and arms, is also termed 'feel' by the driver [Sugitani, Fujuwara, Uchida & Fujita 1997].

This definition coincides with Zaremba, Liubakka & Stunz's [1998] as they write that steering feel is effectively defined by the steering wheel torque the driver senses during steering manoeuvres and by the vehicle response to steering inputs.

These two ideas will be explained in further detail in sections 2.1 for the first concept of the driver as vehicle controller and 2.2 for the feedback experienced by the driver.

1.5 The Scope of the Project

The nature of the term steering feel has been explained in section 1.4 and it is clear that there can be many interpretations of the term. Thus, there are many aspects of the automobile that could contribute to steering feel. It was therefore required to define steering feel in section 1.4 to constrain the topic and concentrate on steering feel in terms of vehicle control quality and feedback. These vehicle properties can be affected by a wide range of parameters such as weight, suspension design, and tyre choice. This thesis focuses on the steering system. Assuming the whole vehicle has inherently good control properties, the influence of the steering system on the steering and control quality is examined.

Chapter 2

Hypothesis

2.1 Vehicle Control Quality and Steering Feel

The entire system is defined as the driver-vehicle-road system as shown in figure 2.1. This is a closed loop model. The system to be operated by the controller comprises the steering, vehicle and road system.

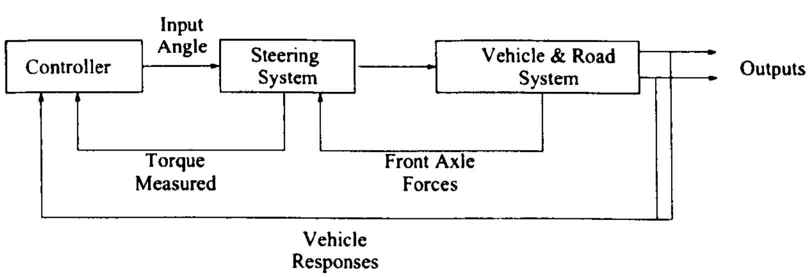

Figure 2.1: The Driver-Vehicle-Road Control System - Closed Loop Control. This concept shows the angle as an input and the torque as an output.

In this system the driver operates as vehicle controller. He has two methods of control, longitudinal and lateral control via the brake/throttle and steering system respectively [Smakman 2000, McRuer, Allen, Weir & Klein 1977]. According to Rasmussen [1983] the behaviour of the human being as a controller can be categorised into one of the 3 following types:

- Knowledge based behaviour: This applies to complex or unexpected situations and demands reasoning and analysis from the controller based on knowledge available or yet to be acquired.
- Rule-based behaviour: This is used for situations familiar from the past for which the controller has built up a repertoire of rules (behavioural patterns), which govern the optimal control method.

- Skill-based: This behaviour level is applied to tasks which have been encountered and practised extensively in the past. The control used then becomes an automatic reflex-like response in a continuous, sub-conscious manner.

Donges [1995] classifies human target-orientated behaviour compared to a three-level model of the vehicle driving task: The navigational, guidance, and stabilisation tasks. The navigational task describes the planning and choosing of a suitable driving route and is therefore assigned to the knowledge-based behaviour. The dynamic control process takes place on the levels of guidance and stabilisation. On the course guidance level, the driver must follow a particular course by applying the appropriate control measures to put the vehicle on this course; this typically occurs in an open loop control mode. The stabilisation level involves the driver keeping the vehicle on course despite any deviation of the vehicle from the desired course and is typically performed by closed loop control.

Which of the human behavioural models the tasks of guidance and stabilisation involve greatly depends on the individual driver and his experience. As the driver increases his experience, he gradually moves from the knowledge-based behaviour area to the rule-based and the skill-based behaviour levels [Donges 1995]. It is also postulated that as the driver becomes more experienced almost all the controller behaviour is in the rule and skill-based areas and that the knowledge based behaviour can be classified as critical, potentially leading to an accident. Thus, the guidance level task is an important aspect concerning driving safety, as it is on this level where the driver operates, using his senses and his experience in the time allowed, to decide on a course of action, which results in a vehicle guidance which may be objectively safe or unsafe. Donges [1995] and Enke [1979] describe the human's qualities in anticipation, which enable the driver to act in advance, compensating for any delays in the vehicle system. Enke [1979] shows that a faster driver response would help the driver to avoid accidents and thus improve safety.

Bergman [1973] refers to the automatic control analogous to control in the skill-based behaviour level as a hypothetic function called the neuromuscular transfer function. It is hypothesised that stored information such as that from muscular outputs and vehicle responses, is utilised to provide a series of automatic muscular responses to certain visual sensations. Thus, the driver subconsciously learns the relationships between the control inputs and responses for a particular vehicle.

The aforementioned conclusions show that the control of a vehicle, as described in the guidance task, is an area of concern for vehicle and road traffic safety. The behavioural modes for these tasks are the skill and rule based levels, where the driver has built up a repertoire of rules or skills from learning the vehicle control properties.

Both the guidance and stabilisation level tasks are performed with a decent degree of safety only by the skill-based and rule-based drivers. Therefore, it is imperative that the vehicle system possesses properties to encourage the learning of these skills and rules with as little difficulty as possible.

Once the learning process has been sufficiently completed, the driver is then operating on the rule-based level or skill based level. The vehicle's standard operating control relationships are known to the driver. Therefore, should these relationships vary, the driver can detect this and thus conclude that something is altered within the system. This enables the driver to receive information from the system. If needs be, he may adapt his control inputs to the new system and its relationships. This is termed system identification.

2.2 Information, Predictability and Steering feel

Forces and signals contained in the term feedback come in two categories. Firstly, there is the useful feedback of information, including that described in 2.1. The second is useless or corrupting feedback. (The corruption is a feedback, which is not directly related to the control or any useful input and therefore cannot be used to gain information about the control properties or internal states of the system.) The ability to extract information from the system is an invaluable feature in terms of the vehicle's ability to forewarn the driver of an alteration in the previously learnt control system relationship.

When driving a vehicle, the controller processes different sensory perceptions to arrive at the correct control input to the system [Prokop 2001]. He uses his knowledge and his perceptions of the feedback from the vehicle to achieve his aim. Without the feedback the control task is more difficult. The workload and reaction time are further reduced where kinæsthetic information, i.e. feedback through force or torque, is available to supplement visual perceptions [Merhav & Ben Ya'acov 1976]. Good [1979] claims that the feedback of disturbance information (disturbance here refers to an excitation force i.e. a system input) through the steering system allows the driver to take corrective action sooner and results in superior task performance.

The references above show that information, in the form of feedback, especially kinaesthetic, supports the predictive and anticipatory capabilities of the human being. These capabilities, which include the receipt and processing of information, increase the vehicle's active safety [Chenchanna 1976, Donges 1992].

A component of steering feel was defined as feedback in section 1.4. Feedback and information to the driver have been described as contributing to steering feel in the past. When Adams [1981] describes steering feel, he writes that the steering should 'tell the driver' what forces are being used to steer the vehicle. He thus defines steering feel as the communication between system and controller. Gies & Marusic [1998] state that the steering system is there as an information source for the driver. Sugitani et al. [1997] state that optimum steering feel is related to how much information a driver obtains relating to the road.

It is therefore postulated that the transfer of information through the steering system increases the controller's predictive capability and thus increases the active safety of the vehicle. It is therefore a component of steering feel and a requirement for steering quality.

2.2.1 Tyre Information

Vehicle dynamics information comes from the tyres through the steering system. The tyres, being the sole interface between the vehicle and the track, have a wide range of important characteristics to communicate. For example: Perceived friction level, road wheel contact and road unevenness. This wealth of information relating to the car's dynamic situation is then used by the driver to make decisions regarding measures to be taken to ensure safety [Pauwelussen 1999]. This information can be typically picked up as a relationship change in the system identification procedure, as described in 2.1.

Non-linearities in the system, when confined to a particular operational area, can in certain cases be constituted as a change in the learnt relationship. This can be used to identify when this operational area is engaged and is thus extremely useful information. One such case is the tyre-road surface interaction. As the tyre reaches its performance limit the side force and aligning moment generated degrade non-linearly. It is a known tyre characteristic that the tyre aligning torques decrease at medium and high slip angles [Stephens & Kohn 1999]. The degradation of these moments results in a collapse of the otherwise almost linearly increasing steering wheel torque. This can be used as a warning signal for the driver if the tyre aligning torque is expressed as a steering wheel aligning torque that results in physiologically suitable forces perceived at the steering wheel [Goes & Fischer 1974]. Stephens & Kohn [1999] state that pneumatic trail, aligning stiffness and Gough Plot shape (the plot describing the tyre's aligning moment over slip angle) relate directly to the tyre component of steering feel. Reynolds [1998] also independently comes to this conclusion while Good [1979] states that steering wheel feel of the aligning torque on the front wheels provides information about the level of control effort supplied to the tyres.

Being the only contact between the car and the road, tyres play an important role in safety and handling. The forces and moments occurring at this interface contain information relevant to the safety and operational envelope of the vehicle. A system with steering feel and quality should be capable of transmitting this information to the controller. Good [1979] sums this up: 'A steering system which provides reliable feedback of tyre aligning torques through steering feel should lead to best overall driving performance because of the information it yields about disturbances and non-linearities in the vehicle dynamic response'.

2.3 Learnability

The learning process described in section 2.1 is used to progress from the knowledge-based behavioural level to rule-based and ultimately skill-based levels. The driver learns by identifying the input/output relationships of the system. He does this by giving a certain input, and awaiting the system output. He is therefore constantly measuring the input required in addition to the system responses. He can then develop a relationship and learn the system. That means that the vehicle dynamic control properties must be free from features that could result in the deterioration of this learned interaction between controller and vehicle.

To make the learning process as simple and un-complicated as possible, the relationships or rules should be simple and undemanding. A simple relationship can be more easily remembered and when learnt, a change is more easily identifiable. A simple relationship can be defined as one which is correlated, single-valued, continuous and consistent. For the rule to be learnable, it cannot continually change i.e. the vehicle behaviour must remain consistent [Wedlin, Tillback & Bane 1992].

Continuity is an important factor. If the rule changes its nature, it must do so gradually, or continuously. If this is not the case and there is an abrupt change, it is difficult or impossible to foresee. Continuity or graduality of the change provides the controller with a gradual warning of an alteration in the rule. When describing continuity, Laurence, Basset, Coutant & Gissinger [2000] use the terms progressiveness and roughness. A progressive vehicle allows the driver to correct his trajectory and a rough vehicle is almost impossible to correct.

The term single-valued refers to an input value corresponding to one output value. If this is not the case, there are multiple values for a particular input and thus the input/output relation is more complicated. For the relationship to have any meaning, there must be correlation between the two values. The output must therefore occur as a result of the input. The control input and output (vehicle response) should have the maximal, sustained relationship to each other [Sharp 1999].

In this section it has been stated what system properties are required for most effective driver learning and thus control of a vehicle system. In addition, these system properties help the controller to operate at a higher level based on skills or rules which contribute to the safety of the vehicle's operation. Based on the definitions in 1.4, these control system qualities described above are also a requirement for good steering feel properties.

2.4 Consolidation and boundaries of the Hypothesis

Summarising the previous sections, the hypothesis can be consolidated as follows: Steering quality and feel are inter-related terms and it can be said that steering feel is a requirement for steering quality. From section 1.4, quality can be described by the input-response relationships of the vehicle system and the subject's perception of this constitutes feel. A second aspect to the definition incorporates the concept of the feedback of information to the driver through the vehicle's responses, particularly at the steering wheel. This introduces an increase in predictability and safety and represents a component of steering feel and a requirement for steering quality.

It is concluded that the car should function as an easily operable and learnable control system with capability for;

1. Rule and skill learning.
2. System identification.
3. The conveyance of system information.

Section 2.3 states that, in order to achieve this, the relationships between the control input and each response should be correlated, single valued, continuous and consistent. Conflicting properties include unnecessary response delays, behaviour inconsistencies and others. In the context of a vehicle steering system, one with good control properties means that the vehicle's reaction is solely in response to the steering input at the wheel. Poor control properties occur when the vehicle response is not directly due to the control input, e.g. a yaw rate response due to road undulations or simply no response to a steering input.

It is postulated that this is the case in the context of steady state conditions and low frequency transients. It is however acknowledged that outside this bandwidth, i.e. at higher frequencies, unavoidable effects, such as those of inertia, could introduce properties conflicting with the hypothesis. This thesis concentrates on the lower frequency range where the vast majority of everyday driving occurs. It is the opinion of the author that the problem of steering feel should first be understood in the most simple circumstances such as quasi-steady manœuvres rather than highly dynamic situations.

2.5 Vehicle Control Quality Experiment

In order to test the hypothesis, an experiment has been designed to damage the inherent control relationships of the vehicle, that is, to damage the relationship between the vehicle inputs, steering wheel torque and steering wheel angle, and the vehicle outputs.

The experiment involves introducing the following features:

- Steering column with play: Results in a steering wheel input without vehicle reaction for up to ten degrees steering wheel angle.
- Extreme elasticity in the steering column: Results in a lesser but continuous loss of motion in the system due to the wind up of the elasticity in the system and thus a response delay.
- Friction on the steering column: Until the friction is overcome there is no vehicle reaction or output due to a steering wheel torque input.
- Friction on the steering rack: The addition of extra friction on the steering rack has a similar effect on the control properties as friction on the column, described above. However, due to the fact that the elastic elements (damping element and torsion bar) are encountered before the steering rack is acted upon, it will increase the 'lost motion' or 'wind up' in the system and will thus affect the steering wheel angle and torque control relationships.
- Steering servo power assistance: An extremely high level of steering power assistance is provided to cause difficulties in the system identification procedure. Torque levels become so low that the controller cannot perceive any change in the level.

The friction and play measures above produce inconsistent system behaviour; for a certain input there is no output at all and for another input the system output corresponds to the input. All measures damage the system identification procedure. If the input measured by the driver does not reflect the output of the vehicle, the correlation is more difficult to learn and a change in that relationship cannot be detected. The single-valuedness is also worsened, due to the increase of hysteresis introduced by friction, play and wind up caused by excessive elasticity when combined with damping.

Through this experimental procedure, it is proposed that it is possible to assess the negative consequences the steering features play, elasticity, friction, and servo assistance have on the control properties of an automobile.

2.6 Summary

This chapter provides the hypothesis to be tested. It proposes a methodology for the analysis and quantification of steering feel and quality. This is a condensation of the hypothesis.

Through the experiment in 2.5 it is postulated that:

- Extra compliance, play, friction and servo assistance can introduce factors such as; response delay, inconsistent system behaviour, discontinuities and double valuedness.
- This damages the inherently good control relationship between the input and the vehicle outputs as defined by the requirements set out in 2.3.
- According to the arguments in sections 2.1 and 2.2 the following conclusions can be drawn: These requirements, not having been met, impede the system's identification capability and incapacitate the system as a provider of information to the controller. Moreover, it prevents the control system from being easily learnable and operable.
- As the above have been postulated in this chapter as the requirements for steering feel and quality, this suggests how the quality can be altered. This then presents the framework for using the control experiment in 2.5 to quantify what is termed as steering feel and quality. This is the objective of the thesis.

Vehicle and Steering Stability

An underlying requirement for steering quality is stability [Sharp 2000]. Both the vehicle as a whole and the steering system must remain in a stable operational state in order for reasonable control to be exercised. Effects such as vehicle yaw instability due to oversteer or excessive steering shimmy can result in almost complete loss of control by the driver. Stability as a requirement is not under scrutiny in this work. The testing and simulation is concentrated at low frequencies where the vehicle and steering system remain stable in all test and simulation circumstances. Stability in the normal driving range is nevertheless a requirement.

Chapter 3

Literature and Previous Work

3.1 Existing Objective Characteristics of Steering Systems

There are very few objective tests used by the motor industry that focus specifically on the steering system. Different aspects of the steering system are measured on rigs. For example, the steering rack forces and the suspension and steering kinematics may be studied but there are relatively few steering tests which would come under the heading 'Vehicle Dynamics', i.e. tests involving the complete driver - vehicle - road system. Most commonly, objective testing is confined to the areas of power steering levels, while effects on handling, control and response are dealt with subjectively.

The effects of the steering system on handling can be examined using standard handling manœuvres such as those prescribed by the International Organization for Standardization (ISO). The following tests can be used to this effect:

- The steady-state circular test procedure [ISO 4138 1996].
- The lateral transient response method [ISO 7401 1988].
- The transient open-loop response test methods [ISO 8725 1988, ISO 8726 1988].
- Braking or power-off during a turn [ISO 7975 1996] and [ISO 9816 1993].
- Severe Lane Change manœuvres [ISO 3888-1 1999].

These standards examine the vehicle handling as a whole and are not specifically tailored to the analysis of steering. The tests deliver objective quantities, however, the question remains as to what quantities represent good quality. Furthermore, although the ISO standards are used in passenger car development, they are not always utilised in the development of the steering system.

Schmalzl [1991] provides a useful tool in the evaluation of the steering system's quality by outlining test methods to objectively evaluate the front axle of a passenger car. A series of tests and a methodology for their interpretation lead to values and plots, which are capable of objectively describing the vehicle front axle dynamics. Although a description of the vehicle and a means of comparison between vehicles were provided, the quality issue was not addressed. Schmalzl's work was a step in the right direction in the analysis of the front axle and can be used as a tool in the analysis of the steering system as will be seen in chapter 4.

A range of tests for the objective evaluation of the steering system is also presented by Ugo & Data [1996]. The steady state circular test, step input and sinusoidal input tests, and complete steer cycles were used to describe the steering system. The determination of quality was made using statistical analysis and regression methods to correlate with the subjective results of a jury. This method of correlation is similar to that criticised in section 1.2, as little understanding as to why parameters correlate with quality judgements is gained.

3.2 Literature

This section focuses on previous work in fields relevant to the thesis, which has not already been referred to. The literature reviewed is grouped under the following categories:

- Straight Line Running and On-Centre Handling.
- Vehicle Handling Quality.
- Steering Feel.
- Simulation.

3.2.1 Straight-Line Running and On-Centre Handling

Straight line running, straight ahead running, and on-centre handling are terms used to describe an area of vehicle handling that has been extensively researched over the years. The first two terms commonly refer to the vehicle's behaviour while remaining on a dead ahead course, while on-centre handling encompasses the region of handling on and just off the straight ahead position, typically including steering inputs up to 20° and lateral accelerations not exceeding 3 m/s^2. In this region of vehicle handling the tyres remain in their linear zone of operation. As most passenger cars spend the majority of their driving time in this region, it is no wonder that it is an area of interest for the motor industry. With the increase in cornering capabilities and handling quality in automobiles, manufacturers are seeking to improve all areas of handling including driving straight ahead. Steering quality and feel play an important role in this on-centre handling quality.

Norman's Weave test

Norman [1984] has made the largest impact in the on-centre handling field with his article eighteen years ago. He defines and uses the 'weave test' on an instrumented vehicle to obtain objective quantities describing the vehicle's behaviour in what he terms the 'On-Center' area. The weave test involves a slow (0.2 Hz) sinusoidal steering wheel input to a vehicle travelling at 100 km/h along a straight road. The objective quantities examined are; steering wheel torque, steering wheel angle, lateral acceleration, and yaw rate. These are presented as a series of cross plots and reduced to a series of steering hystereses, on-centre and off-centre steering sensitivities, torque gradients, and a steering work parameter. A comparison is then made between passenger cars of different manufacturing origin and different steering type. It is evident that the procedure is a useful tool for comparison, but no attempt is made to determine handling quality. Norman's weave test is the best to date in terms of the on-centre region of vehicle handling and it forms the central part of ISO Draft 13674-1 [n.d.]. It is used in this thesis when examining steering quality in the on-centre region.

Farrer [1993] built on the weave test adding a transient and straight line test. On-centre handling was categorised into hand wheel activity, steering feel and vehicle response. The transient and weave tests were used to evaluate steering feel and vehicle response using a similar method of cross plots to Norman [1984]. Correlation of the objective parameters is made with subjective evaluations of these 'on-centre parameters', but correlation to what constitutes quality is not evident. The majority of objective data is collected from the weave test, however, it is observed that the transient test produces results that are closer to subjective perceptions. The transient test involves the vehicle travelling in a straight ahead position and, after settling in the on-centre region, the steering wheel is slowly moved away from on-centre. A form of the transient test, in addition to some of the analysis techniques from this study, form the basis of ISO Draft 13674-2 [n.d.]. A form of this test is used in this thesis for objective evaluation of the steering system.

The weave test was revisited by Higuchi & Sakai [2001] with a new method of analysis of the measured quantities. Curve fits and mathematical functions are used to process the objective data with non-linearity being used as a descriptive parameter. Mathematical expressions were derived from these functions as on-centre parameters. Simulation is then used to predict these parameters. The objective results are compared with subjective evaluation and correlation is achieved for some parameters with the subjects' preferences.

Deppermann [1989] also uses cross plots of quantities such as steering wheel angle and steering wheel moment of low frequency sine steer manœuvres as an objective quantification for on-centre handling. A straight ahead driving test is used in conjunction with a vehicle simulation in this study. With respect to steering feel, it is concluded that, small breakaway torque (torque required to surpass steering friction and thus move the steering wheel) and a large torque gradient over the steering wheel angle are judged to inform the driver better with regard to the steering corrections needed.

Straight Running Tests

A different approach was studied by Loth [1997]. During straight running, the vehicle was subjected to random steering inputs up to $0.4\,Hz$ and the resulting measured quantities were analysed in the frequency domain. It was found that the phase of the transfer function of steering wheel angle to lateral acceleration (a quantity describing vehicle response) should be minimal for optimal on-centre handling. The effect of the friction in the steering system was highlighted as a damaging factor for this measure of quality.

Engels [1995] also describes straight running in terms of frequency, namely the frequency with which steering corrections must be made while driving straight ahead. The frequency of measured quantities relating to the driver input and the vehicle reaction have also been examined by Ehlich, Heissing & Doedlbacher [1985].

Another approach is reported by Dettki [1997]. Here, the yaw rate is measured on a vehicle being driven along a route subjected to random wind disturbances. The steering input is recorded and then input into a bicycle vehicle model. The resulting yaw rate simulation is then compared with the measured rate and the difference is taken as a measure of the precision of the car's straight ahead behaviour.

3.2.2 Vehicle Handling and Steering Quality

A list of criteria for good handling is supplied by Savkoor, Happel & Horkay [1999] in which the consistent feedback of information including steering torque is cited. It is also noted that disinformation or inconsistencies should be avoided and that this area requires further investigation. The sensitivity of the human to changes in vehicle handling, objectively measured as response (yaw rate, side-slip and roll angle) are examined. However, the steering system dynamics are ignored.

Bergman [1973] claims that the role the driver plays in vehicle handling is more important than that of the vehicle response properties. Therefore, it is the ease of vehicle control, and not the ultimate performance capabilities of the vehicle, which contribute more to vehicle handling quality. Furthermore, steering control is highlighted as the principal factor in driver-vehicle handling for severe manœuvres due to the higher driver skill requirement.

3.2.3 Steering Feel

The role of tyres in steering feel has been described in section 2.2.1 and when defining feel and quality, Brindle [1983] and Setright [1999] share the view that the self aligning moment of the tyres perceived as a torque at the steering wheel constitutes good steering feel. Miyamoto, Momiyama & Fujioka [1991] and Nagiri, Doi, Matsushima & Asano [1994] have used this feature to simulate torque feedback to the driver in simulators. It has also been shown that information transmitted by means of a torque, i.e. kinæsthetic information as opposed to visual or audible information, can be processed more quickly by the controller and the workload can be reduced [Bielaczek 2001, Merhav & Ben Ya'acov 1976, Sato, Goto, Kubota, Amano & Fukui 1998, Yuhara, Iijima, Shimizu & Asanuma 1997].

Steering torque is important when dealing with the steering system. It has been mentioned in section 1.4 and will be examined in much detail throughout this thesis. Steering Torque Gradient is the rate of change of the torque with respect to vehicle lateral acceleration, $\frac{\Delta M_H}{\Delta a_y}$. This is a term which is frequently used when discussing steering feel [Norman 1984, Farrer 1993]. The torque gradient with respect to steering angle, $\frac{\Delta M_H}{\Delta \delta_H}$, is also commonly referred to in this context, [Dettki 1997]. Segel [1964] studied the effects of steering torque gradient using subjective evaluation and objective experiments. The optimal gradient could not be found. Only a preferred range of gradients away from the extremes was found. The drivers could not agree on a single optimum. Although the gradient can affect the control properties at extreme levels, its effect at normal operational levels is negligible on performance. Therefore, as an objective measure for quality it is unsatisfactory and will not be studied in great detail in this thesis.

Torque gradient is a feature influenced greatly by steering power assistance. The level and nature of assistance is also often associated with feel. Baxter [1988] defines steering gear feel purely in terms of parameters which describe the power steering mechanism. Anderson [1982] explains feel in terms of forces from the road wheels being transmitted to the driver. An experiment is conducted varying power assistance and a statistical analysis to determine subjective/objective correlation of the test results is performed. Design issues whilst considering steering feel are listed by

Bertollini & Hogan [1999]. Steering effort is described as one of many aspects of feel and is examined with reference to its variation over vehicle speed.

The weave test is revisited by Sato, Osawa & Haraguchi [1991]. Steering feel is defined as the weave test parameters; steering effort, returnability and torque phase lag. The effects vehicle speed has on these parameters was measured. Correlation with subjective evaluation appears inconclusive. Koide & Kawakami [1988] also used the weave test with more detailed subjective evaluation. A complicated analysis was used, which achieved only mediocre results in the correlation of ten sensory evaluations with forty seven measured quantities.

Nakano, Kada, Nishihara & Kumamoto [2000] also use a weave test but, interestingly, measure steering effort directly using Electromyogram measurement on a subject's muscles. Using a definition of steering feel confined to the on-centre region similar to Sato et al. [1991], it was determined that a reduction of steering effort reduces the workload on the muscles while preserving steering feel qualities.

3.2.4 Simulation

The existing literature contains a wide range of steering models used for many different purposes. In fact, there are too many to list. The following references concentrate on steering simulation in the areas of steering feel and on-centre handling, which are relevant to this thesis.

The on-centre handling region of vehicle handling is comprehensively modelled by Post [1995]. A linear bicycle vehicle model, integrated with a characterised steering model and a tyre model, was used to predict on-centre vehicle performance. Characterisation techniques were used in the estimation of non-linear parameters for the steering model. The resulting simulation can accurately predict the hysteresis loops from the weave test developed by Norman [1984]. A similar methodology is applied to the simulation in this thesis.

A multi-body simulation is used by Galvez [2000] when addressing the modelling of straight running quality. The effect of non-linearities in the steering system were also examined but the study is purely theoretical and simulation results are not compared with measurements. Similar modelling exercises using the same simulation package as Galvez [2000], AUTOSIM, were carried out by Kim [1997] and Park [2000].

Roos [1995] models the straight line running on rough roads or 'undulating' road surfaces. The simulation is therefore concerned with vertical forces and displacements in addition to the conventional lateral dynamics commonly studied in the on-centre handling area. The majority of the analysis is in the frequency domain and good correlation is achieved between simulation and measurement. Due to the inclusion of the vertical disturbances, this model is unnecessarily complicated for the task at hand in this project.

Steering feel is addressed by Howe, Rupp, Jang, Woodbur, Guenther & Heydinger [1997] when improving steering simulation for a driving simulator. Two steering system models are presented in an attempt to improve the feedback experienced by subjects in the simulator. There are some good modelling techniques used and detailed representation of the steering system including the power assistance is possible.

Chapter 4

Testing

4.1 Introduction

As described in chapter 2, the hypothesis is to be investigated with the aid of the Vehicle Quality Control Experiment. This is performed by simulation and vehicle testing. This chapter will deal with all forms of testing carried out. Individual components are tested in the laboratory to determine their exact properties when introducing a change to the system and also to provide quantities for the simulation model. Complete vehicle objective testing on the track, and subjective testing by an expert test driver were completed as the quality experiment.

4.2 Vehicle Objective Testing

4.2.1 Design of Experiment

The objective of this thesis is to provide a method for the evaluation of steering quality. The hypothesis in chapter 2 postulates a method by which the quality of the steering system can be altered through modifying the system parameters. The design of experiment is set out to determine if the effects of parameter change are those postulated in the hypothesis. This is most clearly identified when a single parameter change is isolated. Therefore, the experiment operates by altering a single vehicle parameter at a time so that the effects of this parameter only can be fully understood. Loth [1997] also employs this method of experimental design.

Due to the non-linear nature of the system, the parameter variations, when combined, may not be easily calculated from the results of the experiment described. However, it is not an aim of the thesis to find an optimal parameter setup for steering quality. As a result, a complicated design of experiment to cover a wide range of possible configurations is not required.

4.2.2 Consistency Principles

As described in 4.2.1, in each test only one parameter was to be studied. It was therefore necessary to ensure that aside from this parameter all other variables were kept constant to ensure that any effects measured could be attributed only to the parameter variation under study for that particular test.

The most effective method of achieving this was to perform a control measurement on the same day any parameter variation was to be performed. This control measurement took place immediately before the measurement of a particular vehicle variation. Before the control measurement, the car may have been adapted to include any special adjustable parts required. With the vehicle and/or its adjustment at the standard setting, the control measurement was taken. Immediately following that, the adjustment was made resulting in an exact alteration of the vehicle properties and then the vehicle was measured once again, this time with the effects of the altered properties.

This ensured that for each parameter varied, for all the tests, there would be a standard configuration available for comparison with each variation tested. This standard configuration was then exactly consistent with the variation to be measured except only for what was immediately thereafter adjusted.

Consistency was furthermore maintained by the following techniques:

Method of Parameter Variation

In the choice of how to alter the vehicle properties, a great effort was made to find a solution, which altered only the vehicle property in question and, as far as possible, left all other properties unaffected. This principle was also adhered to by Loth [1997]. The method of this parameter variation to influence the vehicle properties is dealt with in 4.2.3 in more detail.

Consistency of External Influences

In order to minimise the extent of external influences, such as weather and track state, on the car, measurements were only completed on 'fair weather' days. That is to say, testing was only carried out in the dry with little or no wind disturbance. As mentioned above, a control measurement of the vehicle in its original form was also performed on the same day. Thus, the effects of weather, track temperature, and surface moisture could be minimised.

All tests were carried out at the BMW test facility in Aschheim just outside Munich. Furthermore, each test for each vehicle state was carried out on the same portions of the particular tracks. This minimised any influence the track surface could have on the measurements.

Vehicle State

General practice throughout the testing was to keep the car as constant as possible. When tyres were changed, those of the same dimension and manufacturer were replaced and run in. After any parts were fitted in the suspension area, the car was measured to ensure that the static values of camber and caster were not altered.

The control measurement also acted as a check. If there was any minor change in the vehicle properties, due to the preparation for a parameter variation, this change was taken into account in the control measurement. Thus, the difference between the control and variant remained solely the result of the parameter alteration.

4.2.3 Altering the Vehicle's Properties by Parameter Variation

Since the method of testing itself was under scrutiny rather than just the effects of each parameter on the vehicle properties, the parameter variations were chosen to be more extreme than would otherwise be carried out in a parameter study. With such large changes being introduced, it was then clearer in the outcome of the tests, whether the test was capable of discerning the alteration in the vehicle's behaviour. Thus, the chances of small differences in the measured outcome being overcome by measurement noise or an external influence were fewer. Furthermore Hoffmann [1968] details the difficulty in the subjective evaluation of small changes in vehicle handling variables.

Variation of the System Elasticity

Included in the steering column is an elastic disc element or Hardy disc (section 1.3.1, figure 1.2). This is mounted in an aluminium bracket which is easily interchangeable. Thus, other Hardy discs of different stiffnesses could be prepared which, when in place of the original component, would alter the elasticity of the steering column. These components were tested separately on a rig to ascertain their stiffnesses (see section 4.3.1).

Varying the System Friction at the Steering Column.

The friction on the steering column was implemented on the column so as not to be affected by the power assistance. This way, a torque must be applied to the steering wheel to first overcome this friction before the column can be turned. As explained in 1.3.1, the torsion bar must first be displaced before the torque can be assessed and power assistance supplied. Since the friction on the column has to be overcome by the driver before the column and torsion bar will rotate, the power assistance cannot work to lessen the effect of the friction.

To implement the addition of steering column friction, a plastic collar was constructed from two solid blocks. These could be pressed against the upper steering column and adjusted. The adjustment was in the form of compressing springs and thus increasing the force between the friction blocks and the steering column. Thus the level of friction could be adjusted. The measurement of this friction is detailed in 4.3.2.

Varying the System Friction at the Steering Rack

Friction was also added to the steering rack itself. Contrary to how the friction on the steering column behaves, the rack friction occurs below the steering gear, torsion bar and elastic element. Thus, two new effects come into play. This is because the torque in the steering column - including the torsion bar and steering element - must first increase to overcome the extra friction located on the rack.

The first effect, the predominant one, is that the torsion bar is subjected to a higher torque and thus triggers the servo assistance to reduce this torque. Therefore, the effect of the extra torque required to apply the control input is greatly reduced.

The second effect is that the higher torque in the elastic element leads to a greater deflection and thus a change in the relationship of steering angle to output.

The end result in this variation is that, due to the compensation of the increased torque in the system by the servo assistance, the effect of adding even a very large amount of friction to the rack is relatively small when compared to adding friction on the steering column.

The friction added to the rack was implemented by increasing the yoke pre-load [Wou, Oste & Baxter 2001] using an adjustable yoke. This custom made yoke was equipped with a screw, which could increase the spring force and thus increase the friction on the rack by a definite amount. This was measured and is described in section 4.3.3.

Introduction of Free-play in the System

A specially made lower steering column was used to introduce play into the system. The part simply included a nut through which the degree of play could be set. This was easily measured as the angle of rotation until contact with the nut was made.

Variation of the Steering Power Assistance

Coming up with a single component, which would alter this property alone and none others was not as simple as with the other variations. To do that, a new steering gear or valve would have to be manufactured. Even then, the properties of different steering valves may not have been identical apart from the level of assistance provided.

The solution to this problem was found using the electronic valve actuation in a Servotronic® steering system developed by the company ZF Lenksysteme GmbH. This is a rack and pinion steering gear similar to that described in section 1.3.1 with the difference that the level of assistance varies with the vehicle speed. This hardware enabled the manual variation of the level of assistance via an electronic control unit (ECU).

The Servotronic® system is shown in figure 4.1. The numbers in parentheses refer to labelled items in this diagram. This system uses a hydraulic transducer valve (3) to alter the valve characteristic and thus change the level of steering torque required to achieve a required hydraulic reaction or assistance.

1	*Electronic Speedometer*	2	*ECU*
3	*Electro-Hydraulic Transducer*	4	*Feed oil radial groove*
5	*Radial groove*	6	*Radial groove*
7	*Return oil chamber*	8	*Reaction chamber*
9	*Reaction piston*	10	*Compression spring*
11	*Cut-off valve*	12	*Orifice*
13	*Ball*	14	*Centreing piece*
15	*Torsion bar*	16	*Valve rotor*
17	*Valve sleeve*	18	*Piston*
19	*Housing*	20	*Pinion*
21	*Rack*	22	*Track rod*
23	*Feed oil control groove*	24	*Feed oil control edge*
25	*Axial groove*	26	*Return oil control groove*
27	*Return oil control edge*	28	*Pressure relief and flow limiting valve*
29	*Steering pump*	30	*Oil reservoir*
ZL	*Power cylinder, left*	ZR	*Power cylinder right*

Table 4.1: Legend for figure 4.1

With maximum current provided by the ECU, the transducer valve closes and prevents the flow of oil from the feed oil radial groove (4) to the reaction chamber (8).

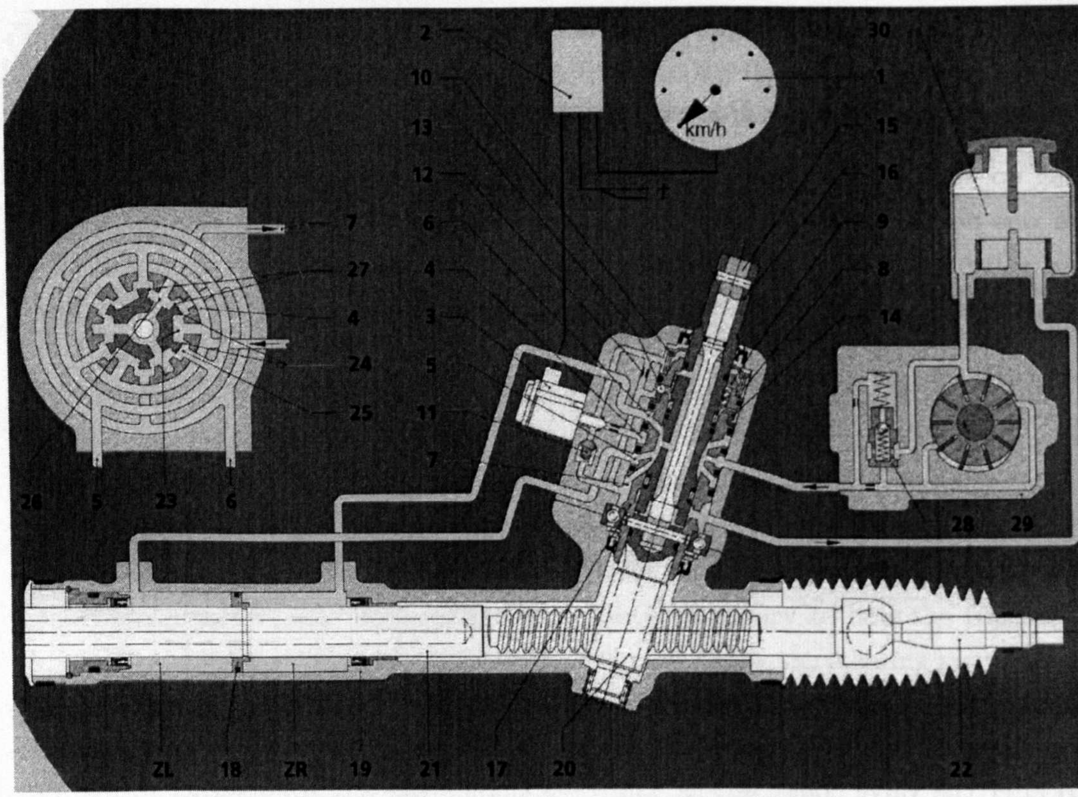

Figure 4.1: Servotronic® Rack an Pinion Steering Gear [ZF Lenksysteme GmbH 2001]

Thus the valve operates as a normal rotary valve, as described in section 1.3.1.

When the current is reduced, the transducer valve opens and allows a limited supply of oil from the feed oil radial groove (4) to the reaction chamber (8). As a result, there is a higher oil pressure acting on the reaction piston (9), providing additional torsional resistance to the valve rotor (16). Thus, the hydraulic reaction requires a higher steering wheel torque until a determined hydraulic assistance is raised in one of the power cylinder chambers (ZR) or (ZL), [ZF Lenksysteme GmbH 2001].

The details of the levels of assistance provided and the measurements of this new steering rack system are dealt with in section 4.3.4.

4.2.4 Manœuvres and Tests

Choice of Testing Methods

The tests and manœuvres are designed to examine the relationships between the input and output of the vehicle system relevant to steering feel. It has been seen in Chapter 3 that the on-centre region is an area focussed on when examining steering feel and quality. Most testing is carried out in the low frequency range (< 1 Hz) with analysis in the time domain. The frequency domain can also be used for analysis especially when dealing with phenomena at higher frequencies. It is acknowledged that there are steering quality issues, especially stability issues, at higher frequencies but it is important that the problem be examined in its simplest form if it is to be understood at all. Steering feel is a phenomenon encountered in everyday, normal driving conditions, where steering inputs are low frequency and highly dynamic manœuvres are not encountered. This governs the choice of manœuvres for the experiment.

Schmalzl [1991] (see section 3.1) produced a comprehensive testing methodology for evaluating the front axle and steering behaviour. This work was examined as a basis for the objective testing. The study included the following manœuvres:

1. Parking Test: This is where the vehicle is stationary with engine idling and the steering wheel is turned slowly from lock to lock. This yields the maximum parking forces.
2. Figure '8': The vehicle is travelling at walking speed and the steering wheel is rotated towards full lock, released and allowed to return to centre of its own accord. This is performed in both directions. The steering returnability is examined here.
3. Constant Steer Angle: A constant steer angle is established while at rest and then the vehicle is accelerated until the limit condition is reached. This is to determine if the vehicle turns in on itself. The test is repeated for different steer angles.
4. Transition Test: Driving at a constant speed and starting from the straight ahead position, the vehicle is steered out of centre by a slow ramp input up to $\pm$ 10°. This test is repeated in both directions at different vehicle speeds.
5. Macro Sine Test: From the straight ahead position at constant speed, a sinusoidal input of $\pm$ 60° at approximately 0.5 Hz is administered. This is carried out at different speeds.
6. Micro Sine Test: This test is similar to the macro sine test, except that the input is reduced to $\pm$ 10° and it is performed at higher vehicle velocities.
7. Stationary Circle Test: This is the [ISO 4138 1996] standard manœuvre.

This program was examined in detail, with all manœvres being driven and evaluated. The transition and micro sine tests concentrate on the on-centre handling region. This field was researched in detail (Section 3.2.1) and it was determined that the ISO working group drafts, [ISO Draft 13674-1 n.d.] and [ISO Draft 13674-2 n.d.], contained the state of the art methods based on [Norman 1984] and [Farrer 1993]. Therefore, items 4 and 6 in the preceding list were replaced by the ISO draft transition test and the weave test respectively.

The Three Principal Tests

This revised program covered a large area of the normal driving range of a passenger car from parking to high-speed motorway travel. While all tests were performed and recorded, three tests were of particular importance and captured the steering feel and qualities more effectively than the others:

1. The transition test:
   The transition test examines the 'out of centre' area of vehicle handling (figure 4.2). This is the area directly from the straight ahead area - where all steering and lateral degree of freedom measurands are zero - into the on-centre region.
2. The weave test:
   This test procedure deals with the handling region where the majority of passenger car driving occurs; the on-centre area (figure 4.2). It covers lateral accelerations up to 3 m/s^2.
3. The steady state circle test:
   The circular test is performed at lateral accelerations up to and including the on-limit behaviour. This represents steady cornering from normal driving through to severe cornering manœuvres.

These test procedures will be detailed and used as the backbone of the objective analysis. The remainder of the tests will not be covered in detail, as they make a relatively small contribution towards the verification of the hypothesis.

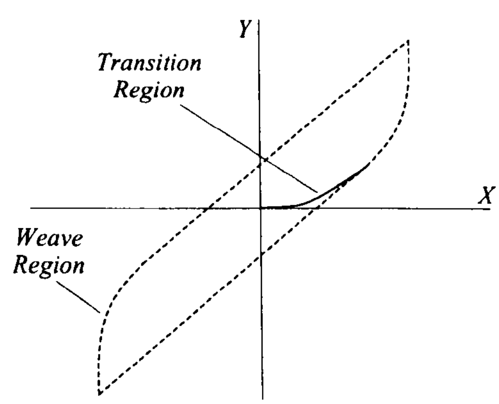

Figure 4.2: An illustration of a cross plot of steering input (X) to vehicle output (Y) detailing the regions of on-centre behaviour examined by the transition test (solid line) and weave (dashed line) test.

The parking, figure '8', and constant steer angle tests yield information on parking forces and returnability. The vehicle must possess certain qualities in these areas. The forces must be within the driver's physical capacity, there must be sufficient steering lock, the steering should return to centre, and the steering should never wind on by itself. However, steering feel quality is rarely encountered in such manœuvres. A driver cannot sit in a parked car and tell how the steering feels. All the terms described in section 1.4 refer to an automobile driving at a moderate speed engaging in dynamic manœuvres generating lateral accelerations. In order to measure this, the manœuvre must involve a measurable input and output. In these low speed procedures there is barely a measurable lateral acceleration. Thus, the relationships between the inputs and the vehicle responses are insignificant to the steering feel problem.

The macro test falls into an 'in between' category. It is performed at relatively low speeds (30 - 80 km/h) in the most linear area of operation for a passenger car. Non-linearities, such as friction or play, and hysteresis are encountered first in the on-centre region. The area of steady cornering right through to the non-linear operating range of the tyres is covered by the steady state circle test. There are relatively few corruptions present in the range of vehicle handling covered by the macro test to affect the quality. The interesting areas where the corruptions or non-linearities occur are at the boundaries of the macro test i.e. the on-centre region and the areas of higher lateral accelerations which are covered by the three tests highlighted earlier. The macro test is chiefly employed to ascertain levels of returnability and friction. Returnability is not of interest with respect to the hypothesis and friction is examined in detail in the principal three tests.

The Transition Test Procedure

This is carried out according to the ISO standard draft [ISO Draft 13674-2 n.d.]. The basics of the test are as follows:

- The vehicle is driven at a constant velocity of 100 km/h.
- The steering wheel is subjected to a ramp input (one which increases in amplitude with a constant angular velocity).
- The input is applied with a smoothly increasing angular velocity not exceeding 5 °/s until the lateral acceleration of the vehicle reaches a minimum of 2 m/s^2.
- The test is performed a number of times in each direction.

The Weave Test Procedure

The procedure is implemented according to the ISO standard draft [ISO Draft 13674-1 n.d.], which is based on Norman's weave test method [Norman 1984]. The basic procedure is as follows:

- The vehicle is driven at a constant velocity of 100 km/h.

- The steering wheel is subjected to a sinusoidal input of 0.2 Hz.
- The steering input shall be sufficient to produce maximum lateral accelerations of 2 m/s^2.
- The test is performed for a duration of 10 such cycles in one continual measurement.

The Steady State Circular Test Procedure

The ISO standard [ISO 4138 1996] method is employed for this test:

- The vehicle is driven on the 40 m Radius Circle at the lowest possible velocity.
- Data is recorded with the steering wheel and throttle position fixed.
- The vehicle is then driven at the next speed at which data is to be recorded.
- Data is recorded at increments of not more than 0.5 m/s^2.
- The steering wheel and throttle positions are to be maintained as constant as possible while data is being taken.
- The 40 m radius path is followed within 0.3 m of the ideal path.
- Data is recorded for a minimum of 3 s over, as far as possible, the same arc of the 40 m radius circle for each speed.
- The value of lateral acceleration is increased in increments until it is no longer possible to maintain steady state conditions.

4.2.5 Quantities Measured

Measurements are made in order to capture the control input to the vehicle and the vehicle response. The input from the controller of interest is the steering input, which can be measured by the steering wheel angle and the steering wheel torque. The other main vehicle responses of interest involve the vehicle's lateral reaction to the input. This is measured by means of the rate of yaw and the lateral acceleration of the automobile. Table 4.2 lists the possible input/output relationships to be considered. Although the steering angle or torque to lateral acceleration or yaw rate relationships can be easily explained as cause and effect, it is not so clear whether the steering torque to angle relationship is causal. Depending on the philosophy taken, whether the driver inputs an angle or torque to the steering wheel, the steering angle can be termed a vehicle output, or a response from the vehicle to a given steering wheel torque input and vice-versa.

Table 4.3, lists the principal quantities measured to be used in the analysis. A full list of all quantities measured, in addition to a description of the configuration of the measurement equipment can be found in appendix A.1.

Input	*Output*
Steering wheel angle	Lateral acceleration
Steering wheel angle	Yaw rate
Steering wheel torque	Lateral acceleration
Steering wheel torque	Yaw rate
Steering wheel angle	Steering wheel torque
Steering wheel torque	Steering wheel angle

Table 4.2: Viable input/output relationships

Quantities Recorded	*Units*
Time	s
Vehicle speed	m/s
Steering wheel angle	°
Steering wheel torque	Nm
Vehicle lateral acceleration	m/s^2
Vehicle yaw rate	°/s

Table 4.3: Measured quantities recorded during vehicle testing

4.2.6 Processing of Test Results

The tests have been carried out in accordance with the control quality experiment outlined in section 2.5. In the processing of these tests an indication of the following features is examined:

- Double valuedness.
- Discontinuity.
- Lack of correlation.
- Inconsistency.

The Transition Test

The correlation between steering input and vehicle outputs is examined in this test. The input/output relationship should be consistent - i.e. similar at different operating points, continuous and progressive in any behavioural change, and correlated. During this test, lateral accelerations do not rise above 3 m/s^2 and the tyres are behaving within their linear performance range. The vehicle is then, essentially, a linear system. Non-linearities in the response are therefore caused by system properties, which have no correlation to the vehicle's reaction. A perfectly linear relationship intersecting the origin (i.e. zero input equals zero output) would signify maximum correlation, continuity and progressiveness, and consistency. Therefore, the quality of the correlation is determined by its proximity to the linear case.

Signal Processing Procedure:

1. The signals are filtered with a 10th order lowpass Butterworth zero-phase filter at 5 Hz (-3db point at 5Hz).
2. Any offsets are removed from the signals at the straight ahead driving position before the manœuvre is initiated.
3. The signals are truncated at a lateral acceleration = 0.2 g.
4. A line is fitted to the truncated curve using the least square difference method and constrained to go through the origin, figure 4.3.
5. The normalised sum of squared errors is used to determine the degree of differentiation of the curve from the linear case.

This method can be automated and used for the analysis of all the relationships examined. This capability allows the procedure to be pre-programmed and conducted quickly and efficiently. It is therefore purely objective and removes the capacity for any bias on the part of the evaluator. Each measurement curve is evaluated in an identical manner. The pre-ordained cut-off point ensures that the evaluation is performed over a specified consistent vehicle behavioural range. The normalised sum of squared errors is then postulated to be a measure of the curve's deviation from the ideal.

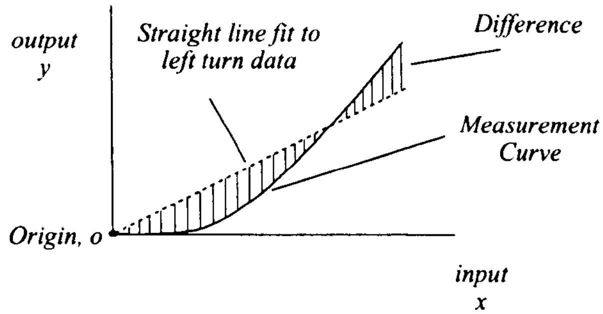

Figure 4.3: Transient Test fitting method.

A different method is employed by [ISO Draft 13674-2 n.d.] using abscissa deadbands. These deadbands come from lines fitted to the data curves excluding 'data that is severely non-linear, such as that in the on-centre region'(figure 4.4). Determining which data to use for the fit and which 'severely non-linear' data to neglect for each curve is left open to the evaluator analysing the data. This is therefore uncontrolled, subjective, and can lead to inconsistent processing. There can also be circumstances where a near linear result yields large deadbands. This result could then be interpreted as low in quality. An example of this is postulated in figure 4.5. Two curves have identical deadbands and gradients, yet curve (2) is clearly less continuous, progressive, and linear than curve (1).

Both methods outlined have their advantages. The ISO method can yield more information as to the source of the non-linearities but the proximity to linear method proved more reliable and consistent and removes subjectivity on the part of the operator. For these reasons, the proximity to the linear case method was used in this thesis.

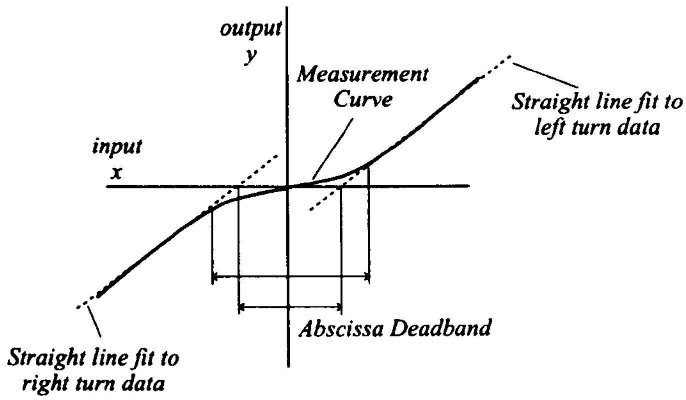

Figure 4.4: The ISO Draft Transient Test fitting method

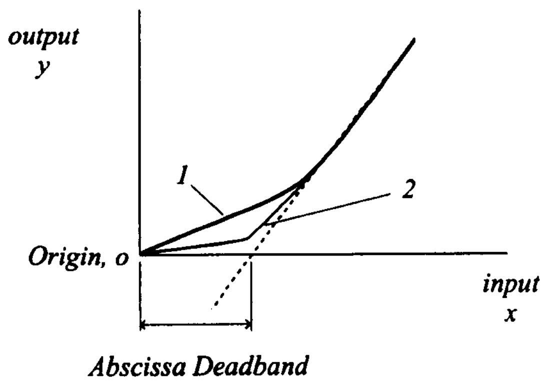

Figure 4.5: The ISO Draft Transient Test fitting method: Example of possible shortcomings

The analysis of the test will be performed on plots of the controller's input against the vehicle output. The input can be of the form of a steering wheel angle, or steering wheel torque. Therefore both cases will be examined. The steering torque/steering angle relationship is also examined as it constitutes feedback to the driver. The vehicle output takes the form of vehicle lateral acceleration and yaw rate. The following plots will be used to analyse and evaluate the transition test:

1. Steering wheel angle vs. Lateral acceleration.
2. Steering wheel angle vs. Yaw rate.
3. Steering wheel torque vs. Steering wheel angle.
4. Steering wheel torque vs. Lateral acceleration.
5. Steering wheel torque vs. Yaw rate.

Weave Test

The Weave test also deals with the on-centre region and the processing is similar to that of the transition test. The same quantities are examined for similar reasons. The data analysis takes the basic form of the ISO standard draft, [ISO Draft 13674-1 n.d.]. where the quantities are examined as cross plots. However, the quantities extracted from these plots are based on, not only [ISO Draft 13674-1 n.d.], but also [Norman 1984] and [Farrer 1993]. Additional quantities are also examined.

The extraction of characteristics from the cross plots is on the basis of the gradients, and deadbands (figure 4.6). The time histories of the recorded data are first processed.

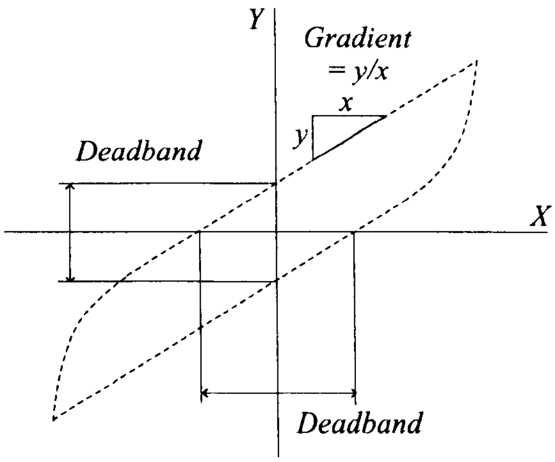

Figure 4.6: The Weave Test Cross Plot Processing

Signal Processing Procedure:

1. The signals are filtered with a 10th order lowpass Butterworth zero-phase filter at 5 Hz (-3db point at 5Hz).

2. Any offsets are removed from the signals so that the average of the signal is zero.

3. Data for at least 10 steer cycles is examined using cross plots.

4. Gradients are determined by fitting a line to each cycle of the data over a specified range using the least square difference method.

5. Excluding the maximum and minimum gradients, an average is calculated from the remaining gradients.

6. A similar average is calculated for deadbands.

The cross plots used for the analysis of the weave test are:

1. Steering wheel torque vs. Steering wheel angle.

2. Steering wheel torque vs. Lateral acceleration.

3. Steering wheel angle vs. Lateral acceleration.

4. Steering wheel angle vs. Yaw rate.

Double valuedness is examined using the deadband values. The non-linearities and lack of continuity are highlighted by the change in relationship in the on-centre and off-centre behaviour. This is identified through the analysis of the gradients , a method also highlighted by Kurachi, Okamoto, Saito & Chikuma [1983]. Non-linearities can also be examined in their own right. A method of non-linearity analysis using fitting and the examination of the first few order terms of the expanded Fourier series was investigated. As Higuchi & Sakai [2001] also demonstrated, fitting methods can be employed to investigate the non-linearities. However, the simpler method of examining the differences in on and off-centre gradients, as employed by Norman [1984], Farrer [1993], and Kurachi et al. [1983], represents a sufficient description of the non-linear behaviour with particular reference to the continuity. This analysis, in addition to the transition test analysis, provides the necessary evaluation of the continuity and consistency features of the hypothesis.

For all the cross plots, the deadbands on both axes were calculated. The gradients were determined and the ratio of the on to off-centre gradient was calculated. All values used by Norman [1984] and Farrer [1993] not already included in this analysis were additionally calculated. Table 4.4 lists all values calculated from the cross plots and figure 4.7 shows an example of how the values can be calculated from a plot. In figure 4.7 the steering stiffness is given by $y1/x1$ while the steering stiffness at 10° is $y2/x2$. The steering stiffness ratio is then defined as the steering stiffness (at 0°) divided by the steering stiffness at 10°.

Steering wheel torque vs. Steering wheel angle

Quantity Calculated	Norman/Farrer Descriptor *New Descriptor in Italics*
Gradient at 0°	Steering stiffness
Gradient at 10°	
Ratio of the above	*Steering stiffness ratio*
Deadband at 0°	Friction *deadband*
Deadband at 0 Nm	Torque deadband
Torque at 0°	Steering wheel torque at 0°

Steering wheel angle vs. Lateral acceleration

Quantity Calculated	Norman/Farrer Descriptor *New Descriptor in Italics*
Gradient at 0.1g	Steering sensitivity
Minimum gradient between ± 0.1 g	Minimum steering sensitivity
Ratio of the above	Steering compliance effect
Deadband at 0 g	*Acceleration deadband*
Deadband at 0°	*Steering angle deadband*

Steering wheel torque vs. Lateral acceleration

Quantity Calculated	Norman/Farrer Descriptor *New Descriptor in Italics*
Gradient at 0 g	Road feel/directional sense
Gradient at 0.1 g	Road feel just off straight ahead
Ratio of the above	*Road feel ratio*
Deadband at 0 g	*Coulomb friction deadband*
Deadband at 0 Nm	*Returnability deadband*
Lateral acceleration at 0 Nm	Returnability
Torque at 0 g	Coulomb friction
Torque at 0.1 g	Steering effort

Steering wheel angle vs.Yaw Rate

Quantity Calculated	Norman/Farrer Descriptor *New Descriptor in Italics*
Gradient at 0°/s	Yaw rate response gain
Gradient at 2°/s	
Ratio of the above	*Response gain ratio*
Deadband at 0°/s	Response deadband
Deadband at 0°	*Steering angle deadband for Response*

Table 4.4: Values calculated from the Weave Test cross plots

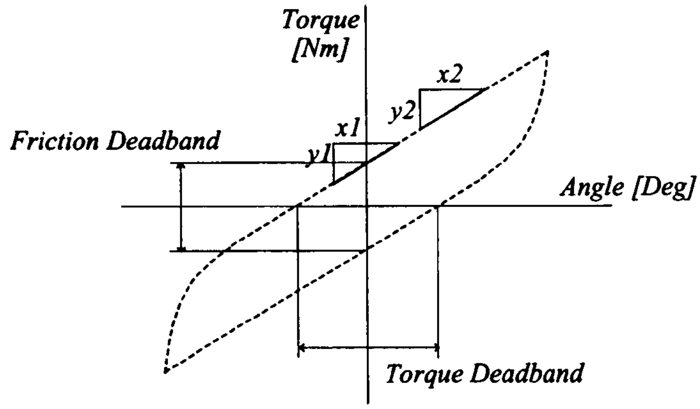

Figure 4.7: A Worked Example of the Weave Test Processing

The Steady State Circular Test Procedure

The processing of this manœuvre is described in detail in the ISO standard, [ISO 4138 1996]. This method is adhered to in this thesis. The particulars governing the processing are as follows:

- The steady state values for all measures are established as the average values of these variables in the time over which the steady state conditions were maintained and recorded.
- The least square difference method was utilised to fit polynomial curves to the resulting data points as a visual aid only.
- The data points are retained, as the fitting exercise is predominantly used to aid the visualisation of the trend.
- Steering wheel angle is plotted against lateral acceleration
- Steering wheel torque is plotted against lateral acceleration

The circular test is used to investigate the non-linear region of vehicle handling governed by the non-linear behaviour of the tyres (see section 2.2.1). This tyre behaviour provides additional information to the driver, which aids safety and the control of the vehicle. This feature thus represents the presence of steering feel and quality and is examined through this test. Therefore, the steering torque relative to the lateral acceleration is analysed. Evidence of the non-linear tyre effects is examined in the near limit behavioural region. The extent to which this behaviour affects the torque relationship is evaluated to determine if it is discernible by the driver.

This phenomenon produced by the tyres was examined in more detail using the quasi stationary circular test procedure. This is a form of the steady circular test where the lateral acceleration is continually but slowly increased, as opposed to using distinct increments. This was to analyse the progressiveness and continuity in the non-linear behavioural region created by the tyre's non-linear saturation. The quasi stationary test yielded a much greater number of data points and thus provided a more detailed description of the near limit behaviour. A method of circle fitting was employed by Laurence et al. [2000] to measure the progressiveness of the steering wheel angle vs. lateral acceleration curve. This method was adapted for use on the steering wheel torque vs. lateral acceleration result. However, due to the dynamic nature of the on-limit behaviour, the repeatability of this test at the limit was found to be unacceptable. It was then decided to use the more common steady state test to improve repeatability. This detailed analysis of the progressiveness of the near limit region is of interest with reference to continuity and progressiveness. Using different parameter variations to affect this, it could be an avenue, which would benefit from further study.

4.3 Component Testing

To change the properties of the steering system as described in section 4.2.3, certain components were altered or modified. An effort was made so that the modification altered nothing but the single property to be studied. Each modification was measured in the workshop laboratories to determine the extent to which each parameter was altered. This information could then be input to the vehicle model to obtain the theoretical influence the property exerts on the system.

4.3.1 Elastic Disc Element

The elasticity of the steering column is contributed by two elastic elements, the torsion bar and the Hardy disc (section 1.3.1, figure 1.2). By replacing the Hardy disc with one more compliant, the stiffness could be reduced. Conversely, by replacing the rubber Hardy disc with one of aluminium, the compliance could be removed.

The measurement of the column stiffness was carried out by mounting the Hardy disc and lower portion of the steering column on a rig. The column is then subjected to a torque of $\pm 6Nm$. The corresponding rotational angle is recorded and a hysteresis is produced as in figure 4.8. The stiffnesses of the two Hardy discs used in the experiment are detailed in table 4.5.

Configuration	Stiffness
Standard disc	3.15 Nm/°
Compliant disc	0.69 Nm/°

Table 4.5: Hardy disc stiffnesses

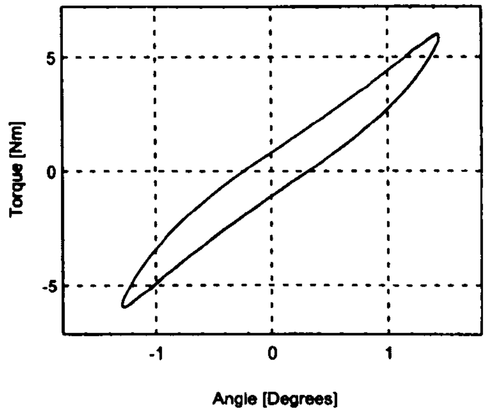

Figure 4.8: An example of a Hardy disc measurement result.

4.3.2 Steering Column Friction

Increasing the friction on the column was simply achieved by the addition of a high density plastic collar. Through adjustable springs, the force pressing the plastic onto the steering column could be increased. This collar was then fixed rotationally relative to the vehicle. Thus, when the column was rotated, the collar remained fixed and there was a resulting friction force between the column and the collar. The adjustable springs provided a method by which the force between the collar and column could be varied.

Measurement of the friction force in the steering column was executed via a measurement steering wheel. This wheel, placed on the steering column, could measure the angle turned and the torque required to turn the column. The steering column was free to move and disconnected from the steering rack. The friction levels measured are displayed in table 4.6.

Configuration	Spring Adjustment	Friction Level
Standard	-	0.1 Nm (10 Ncm)
Half Max.	15 mm	1.5 Nm (150 Ncm)
Max.	10 mm	2.5 Nm (250 Ncm)

Table 4.6: Levels of column friction

4.3.3 Steering Rack Friction

Section 1.3.1 explains how a yoke pre-load is used to press the pinion to the steering rack. This creates friction between the yoke and the rack and between the rack and the pinion. Therefore, by varying the pre-load, the friction on the rack can be altered.

This was achieved using an adjustable yoke.

The measurement of rack friction was performed in the steering laboratory under conditions representing those in the vehicle. The steering rack was connected to a steering pump with the oil flow set to 7 l/min. The temperature of the hydraulic fluid was maintained at 50°. The pinion was then turned from lock to lock and the resulting translational force on the rack was measured. Thus, the force required to overcome the friction on the rack could be quantified. The results from this procedure can be found in table 4.7.

Configuration	Yoke Adjustment	Rack Force
Standard	8.7 mm	120 N
Half Max.	4.6 mm	380 N
Max.	3.7 mm	500 N

Table 4.7: Levels of rack friction

4.3.4 Power Steering Valve Characteristics

The Servotronic® steering system used to vary the level of power assistance was described in section 4.2.3. By adjusting the current delivered to the electro-hydraulic transducer (section 4.2.3, figure 4.1), the degree of assistance delivered by the hydraulics could be controlled.

In order to measure the characteristics of this steering gear and model the different levels of assistance provided, it was measured in the laboratories of ZF Lenksysteme GmbH. The rack was set up in conditions mimicking those during operation in the vehicle; the oil temperature was 50° and flowed at a rate of 7 l/min. The rack was constrained from moving and the pinion was rotated at a speed of about $1°/s$. The torque required to do so was measured, as was the hydraulic pressure where the fluid from the pump enters the steering gear. This delivered a relationship between the torque applied to the pinion and the pressure provided by the power assistance. Through the torsion bar stiffness, a relationship for angular rotation and hydraulic pressure may be derived. This measured relationship is shown graphically in figure 4.9.

4.3.5 Introducing Play into the System

The lower steering column was cut and rejoined with a bearing, which allowed the free rotation of both parts of the column relative to each other. Through a system of pins, the angular rotation of this bearing could be blocked. The relative rotation of

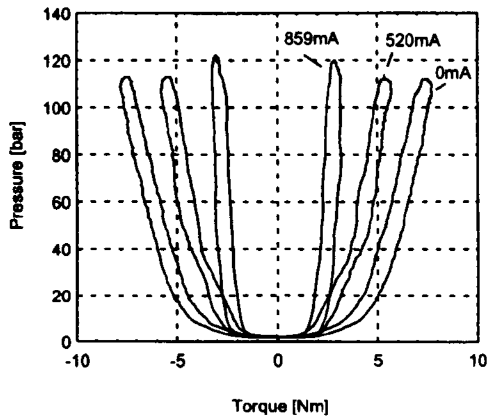

Figure 4.9: Measurement of hydraulic power assistance characteristics. Torque measured at torsion bar, pressure measured at entrance to steering gear.

the column above and below the bearing was unconstrained until the blocking pin was encountered. The clearance between the blocking pins could be adjusted by means of a nut. Thus, a measure of play in the column could be easily introduced and varied.

4.4 Vehicle Objective Testing - Results

4.4.1 Effect of Extra Compliance

The compliance in the steering column was altered as described in 4.3.1. The term 'Compliant' denotes the substitution of the standard Hardy disc with a more compliant one and the term 'Stiff' is used where the Hardy disc has been replaced by a rigid connection. 'Standard' denotes the vehicle's standard configuration without any change.

The Weave Test

Examining the hysteresis for the three variations in figures 4.10, 4.11 and 4.12, there is little obvious effect from the change in system stiffness.

A discernible difference is first noticed when examining the characteristic values from the steering torque vs. steering wheel angle plot (figure 4.13). As the stiffness is reduced, more steering angle is required to produce a given reaction. This increases the torque deadband, and thus the double valuedness, and is evident in the steering stiffness parameter, which describes the gradient at zero angle. However, since the stiffness throughout the entire operational range of the weave test is altered, it has little effect on the steering stiffness ratio (table 4.4), an indicator of continuity and linearity.

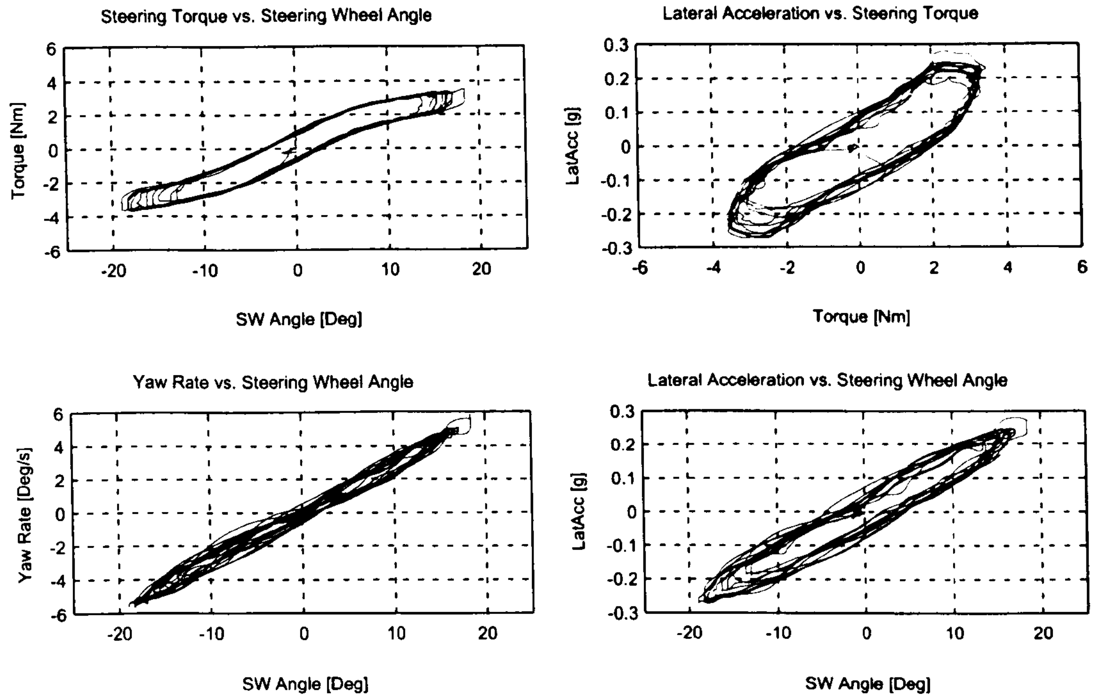

Figure 4.10: Weave test cross plots - **Standard Vehicle Configuration**.

The same effect of the increase in steer angle is evident from the steering angle vs. lateral acceleration plot (figure 4.14). The steering sensitivity term increases with extra compliance as does the acceleration deadband. Due to the global alteration of the elasticity, the minimum steering stiffness similarly increases resulting in little effect on the ratio. Although this ratio is termed steering compliance effect by Norman, it evidently does not reflect the increase in compliance here. The steering sensitivity term also suggests that the most compliant variation is, somewhat paradoxically, the most sensitive. These terms were taken from Norman's work purely as labels for the objective quantities since they are known in the field of on-centre handling. They are not intended as accurate descriptors.

Again, the increase in angle required to produce a reaction is evident here in the steering angle/yaw rate relationship (figure 4.15). The yaw rate response gain is reduced with added compliance. This, being more evident than in the steering angle/lateral acceleration relationship, affects the yaw rate response gain ratio. The effect here is one of lost motion due to the increased elasticity coupled with the friction effects and is captured by the response deadband term. A similar, but more extreme, case of lost motion is seen when examining the effects of free play (section 4.4.5).

The relationship between steering torque and lateral acceleration is barely affected by this parameter variation. A change in elasticity does not affect the force required to

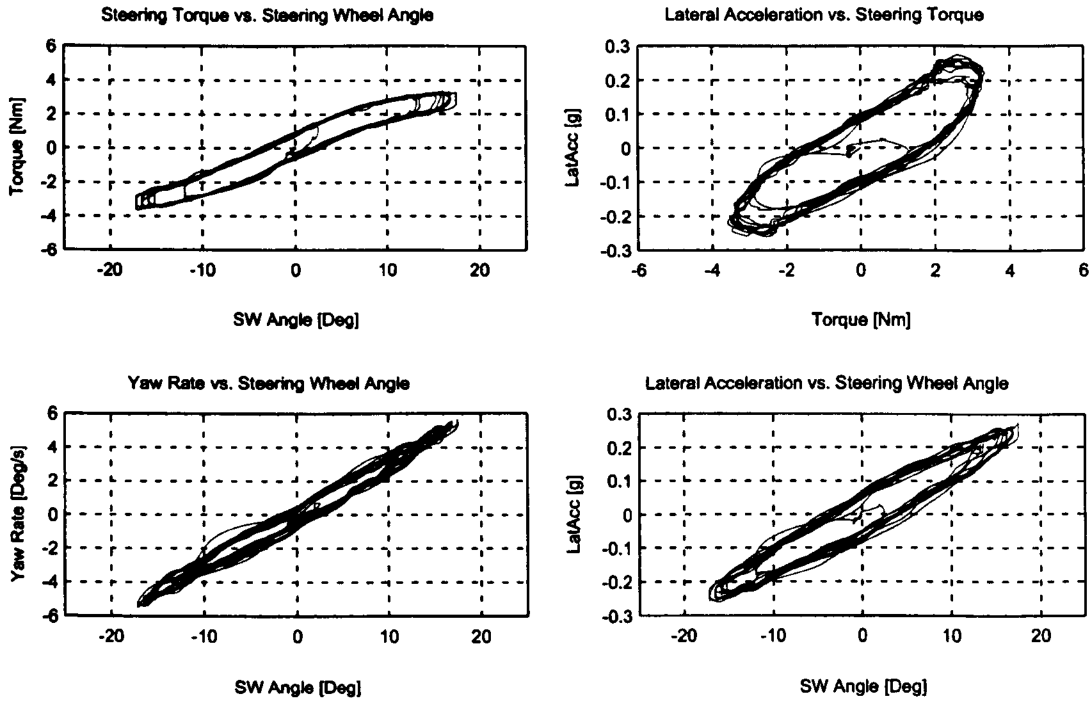

Figure 4.11: Weave test cross plots - **Maximum Stiffness in steering column.**

produce a reaction and therefore, there is little to be deduced from the characteristics from figure 4.16.

The elasticity was varied to an extreme degree, with the least stiff variation five times as compliant as the standard version. The extent to which this affected the continuity, and double valuedness of the system is minimal when considering the extreme variation of the parameters. Although the gradients were visibly different, the continuity, observable via the characteristic ratios, was altered only slightly and the double valuedness was only marginally increased.

The Transition Test

Figure 4.17 shows the results from the transition test for the case of maximum stiffness and maximum compliance, each with their respective reference measurements of the standard configuration (as the cases of maximum and minimum stiffness were tested on different days along with a standard configuration measurement on each day). The range by which the stiffness could be altered, detailed in section 4.3.1, was limited by the fact that the Hardy disc was already very stiff relative to the torsion bar. Therefore, increasing the stiffness by removing it increased the column stiffness by only a small amount. However, since the compliant Hardy disc's stiffness was comparable to that of the torsion bar, the column stiffness could be reduced significantly. This is

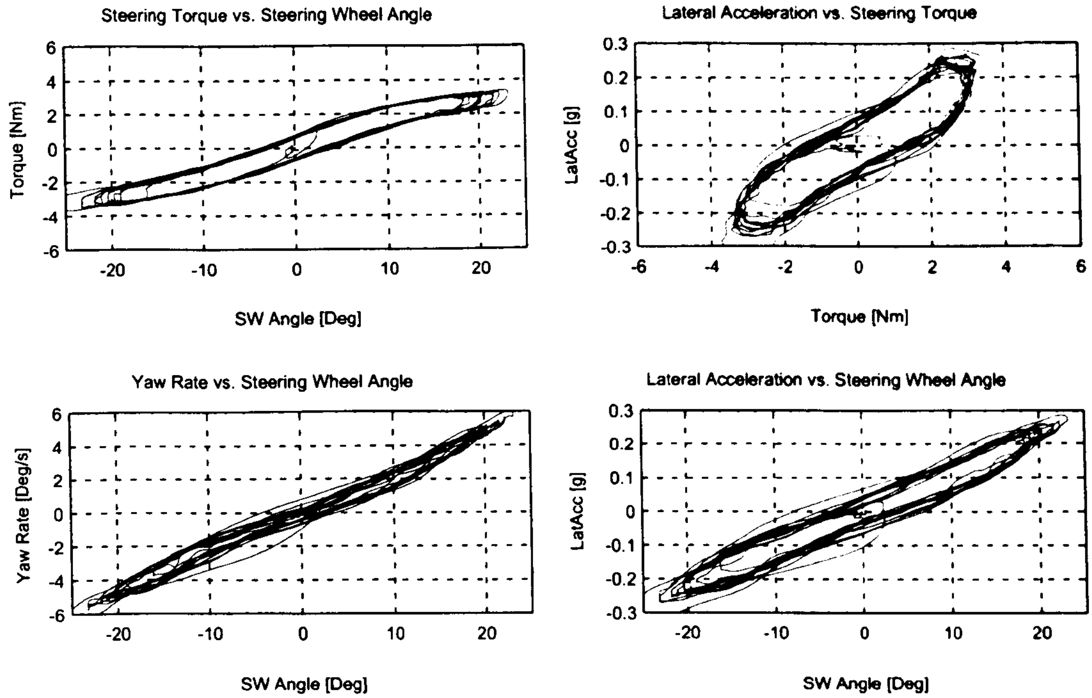

Figure 4.12: Weave test cross plots - **Maximum Compliance in steering column.**

evident in figure 4.17, as it is the only measurement which stands out. Examining the difference from the linear case (the figures in the legend), it can also be concluded that the case of maximum compliance deviates significantly more from the linear than the stiffer configurations. In figure 4.17 some measurement curves cross the x-axis and initially show a negative output before increasing. This is a result of the filtering process which can introduce a slight curve where the correct result should be flat and should not cross the x-axis in this manner.

Stationary Circle Test

The circular test was employed to examine the overall steering torque response in the medium to high lateral acceleration range. Particularly, evidence of the non-linear behaviour of the tyres was examined. This behaviour reduces the steering torque output as the limit is approached and is a useful source of information to the driver (section 2.2.1). As mentioned in section 4.2.6, the detailed analysis of this phenomenon was not pursued, instead the overall torque levels and evidence of this phenomenon are of interest.

On examination of figures 4.18 and 4.19, the non-linear tyre behaviour is obvious in the drop-off of the steering torque at high lateral acceleration. The overall torque levels are similar and thus, little difference is seen between the variations. The differ-

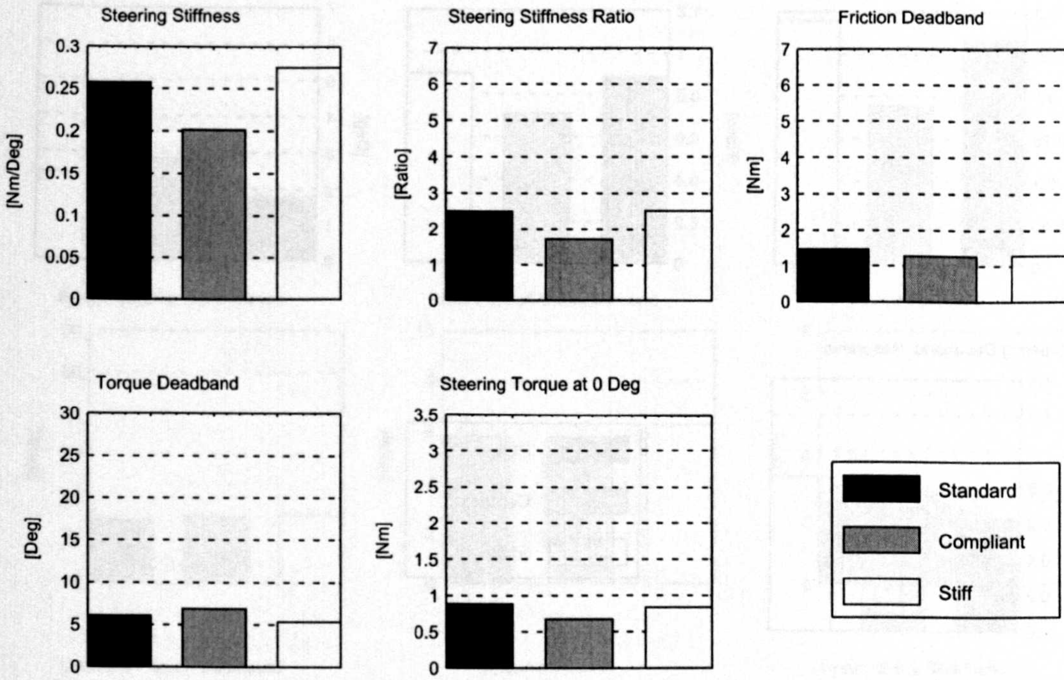

Figure 4.13: Weave test characteristic values - Steering wheel torque vs. Steering wheel angle.

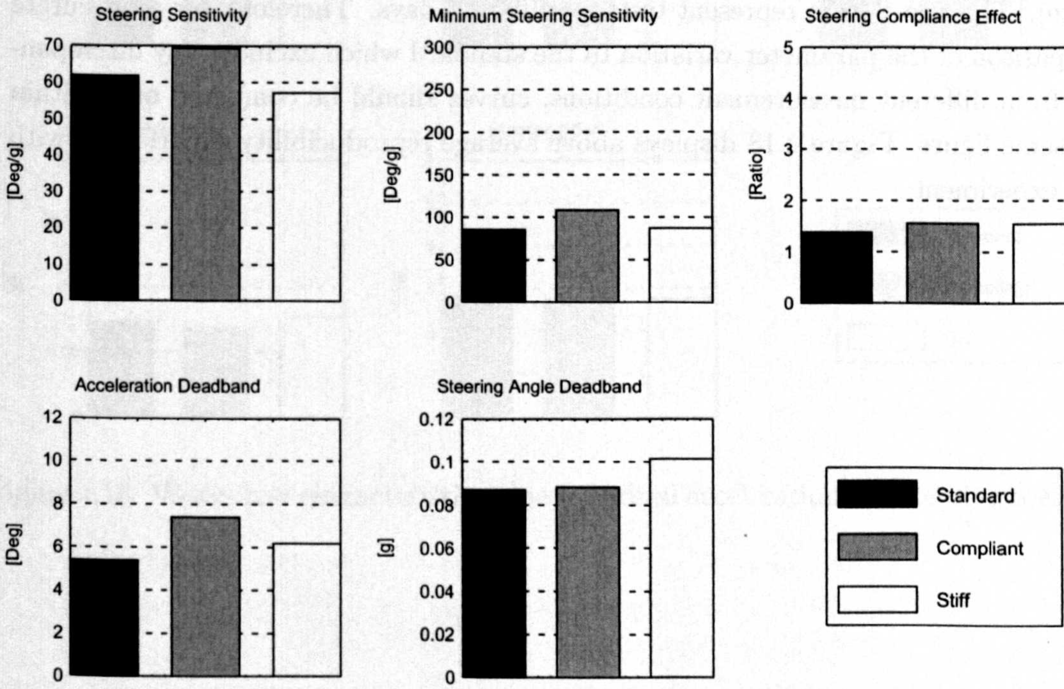

Figure 4.14: Weave test characteristic values - Lateral acceleration vs. Steering wheel angle.

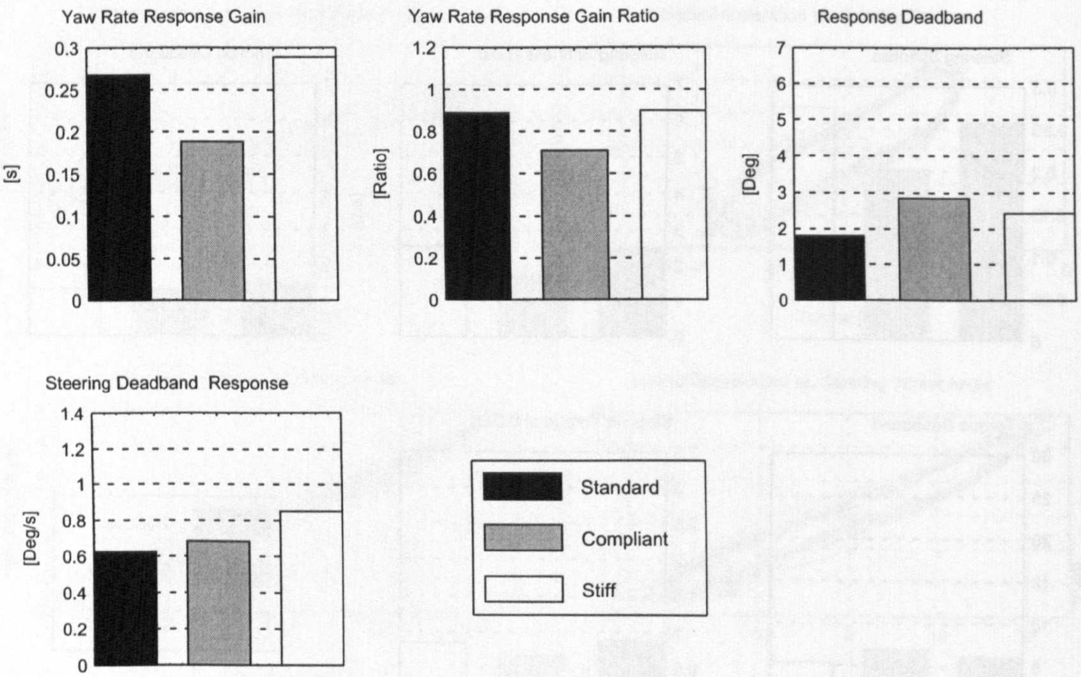

Figure 4.15: Weave test characteristic values - Yaw Rate vs. Steering wheel angle.

ence between the two figures and between the two curves in figure 4.19 is due to the reproducibility difficulties of the test. (This discrepancy is distorted by the fitted line, which is merely a visual aid to help envisage the relationship across the acceleration range). The two figures represent tests on different days. Therefore, for an accurate comparison of the parameter variation to the standard which excludes any discrepancies from different measurement conditions, curves should be compared only within the same figure. Figure 4.18 displays above average reproducibility experienced with this experiment.

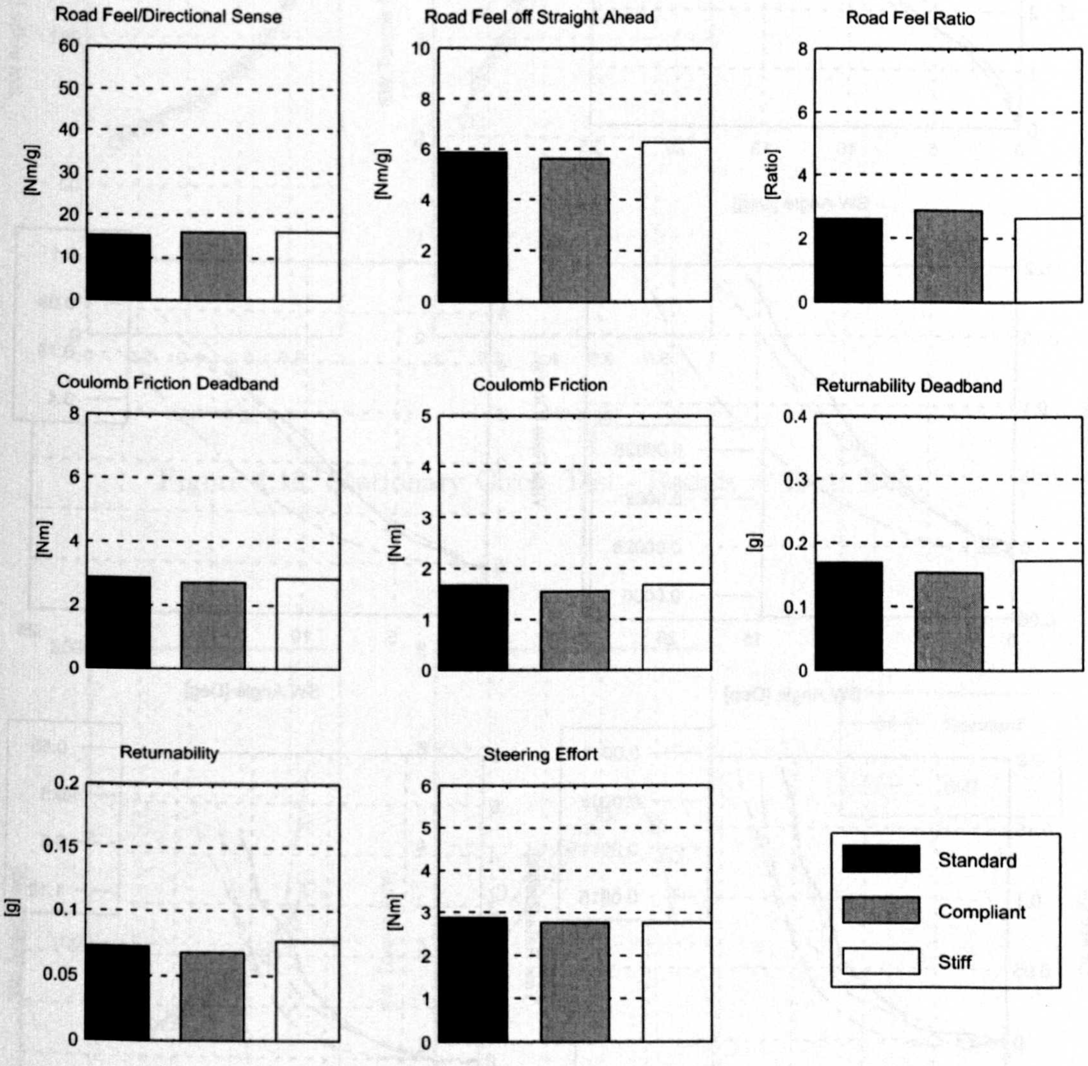

Figure 4.16: Weave test characteristic values - Lateral acceleration vs. Steering torque.

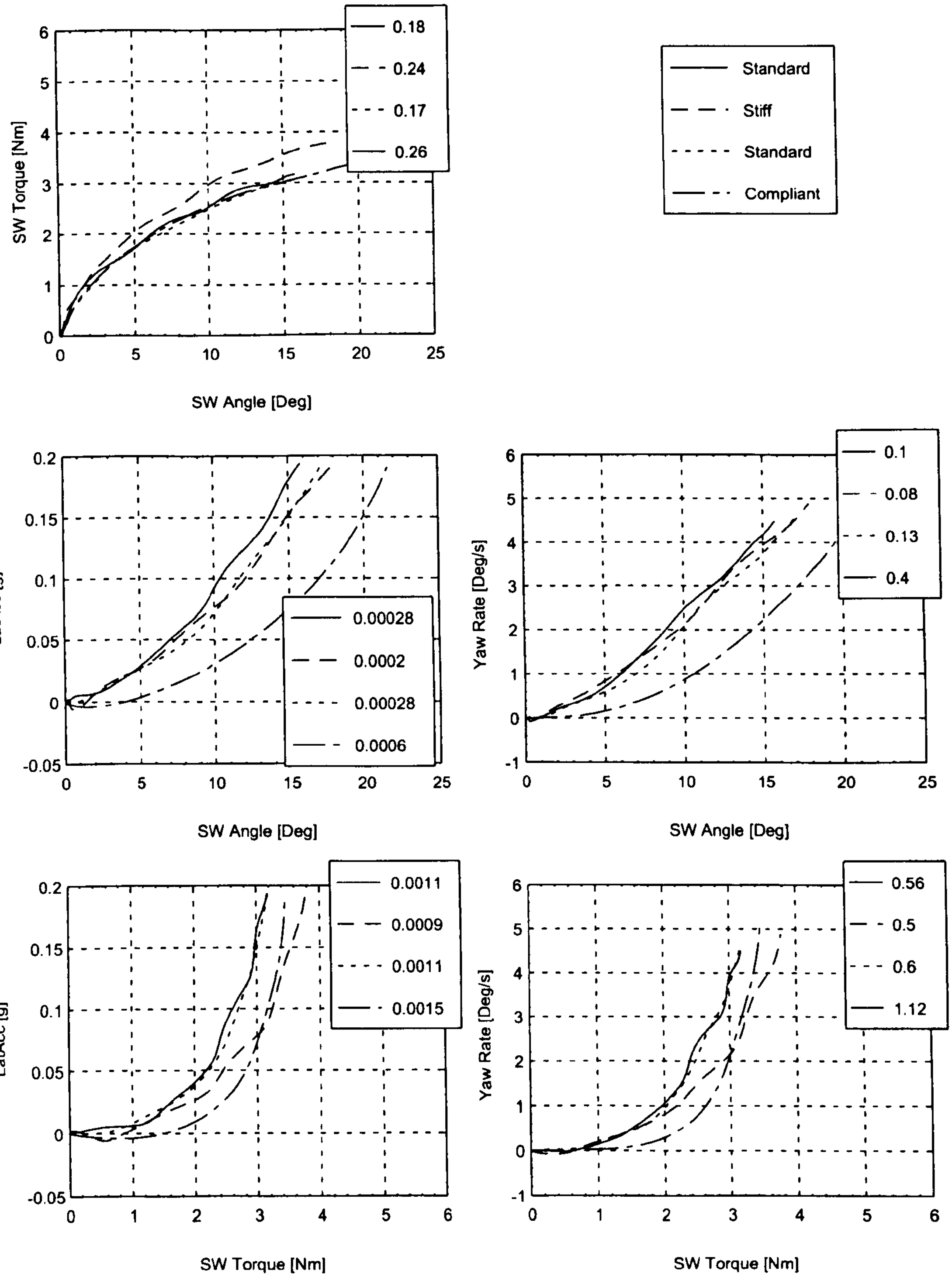

Figure 4.17: Transition test - Figures in legends denote normalised difference from the linear ideal in units of the respective plot's y-axis.

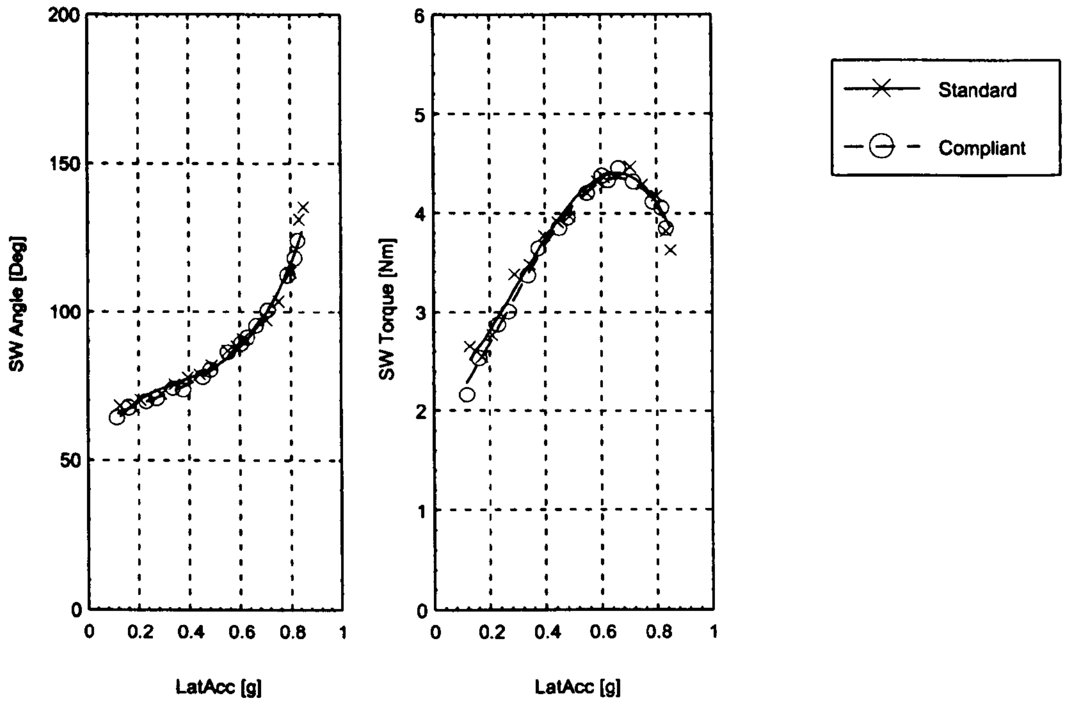

Figure 4.18: Stationary Circle Test - Radius = 40 m, Left.

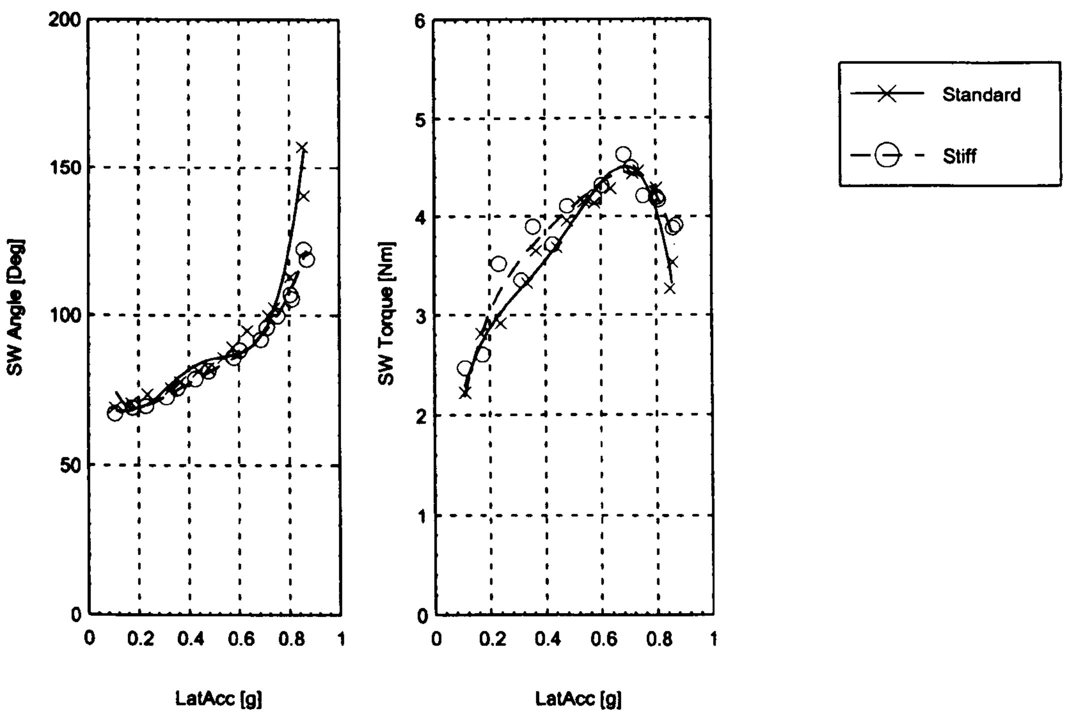

Figure 4.19: Stationary Circle Test - Radius = 40 m, Left.

4.4.2 Effect of Extra Column Friction

Friction was first added at the steering column. This acted directly on the steering wheel as it and the column are rigidly connected. Section 4.3.2 refers to the type and the quantity of friction added. '+250Ncm Col' denotes the largest increase in friction, with '+150Ncm Col being an intermediate value.

The Weave Test

On examining the cross plots, the friction effect is noticed immediately by the widening of the hysteresis of the cross plots containing the steering torque (figures 4.10 and 4.20). This is a common and predictable effect of friction (figure 4.20). Looking at the steering torque vs. angle plot, the effect of the friction is to increase the overall torque levels uniformly over the range. Therefore, the gradients remain largely unchanged and the differences appear in the friction and torque deadband terms (figure 4.21).

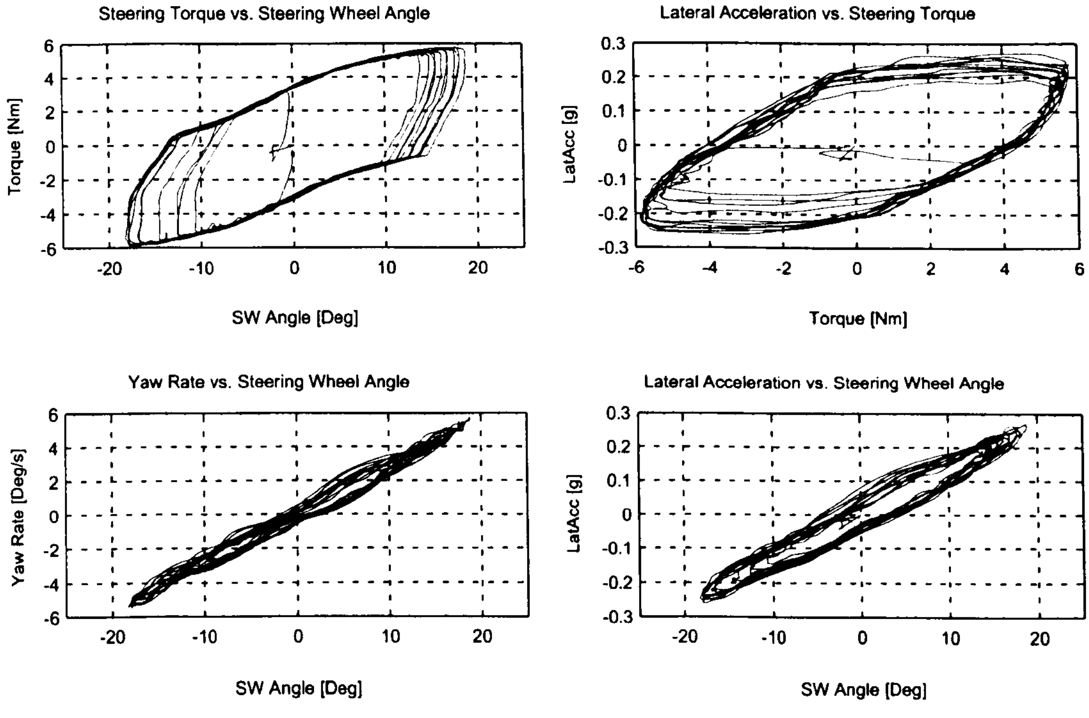

Figure 4.20: Weave test cross plots - **Maximum Column Friction**.

The friction acts on the column and as a result increases the levels of torque required to rotate the steering wheel which is rigidly attached to it. Once the column is rotating, there is no difference in the system properties between the column and the road wheels and therefore the relationship between the steering angle and the road wheel angle is unaffected. Therefore, the friction on the column does not affect the steering angle/vehicle lateral reaction properties. Looking at figures 4.22 and 4.23, which refer to these properties, it is evident that there is little perceptible change in

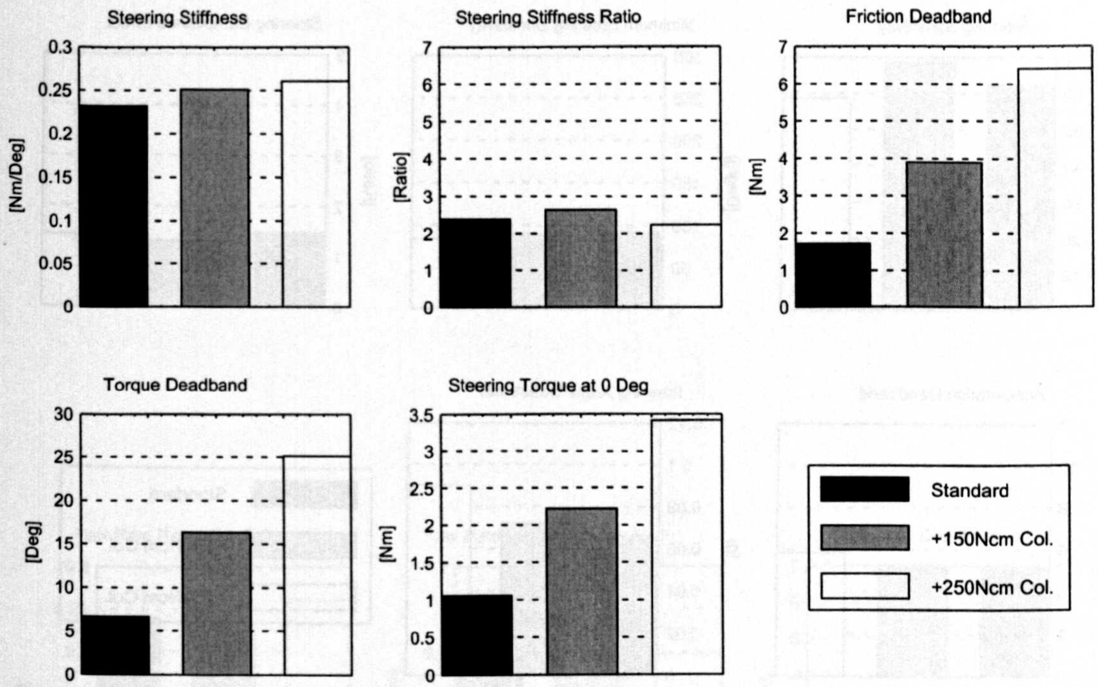

Figure 4.21: Weave test characteristic values - Steering wheel torque vs. Steering wheel angle.

the characteristic values, despite the extreme friction in the system.

As expected, upon examination of the steering torque/vehicle reaction characteristic values (figure 4.24), this relationship is severely altered. Again, the uniformity of the increase of the friction over the operating range has little effect on the gradients but the deadbands are dramatically widened, heightening the double valuedness.

The Transition Test

The column friction is clearly noticed in this test upon examination of the plots in figure 4.25 which show steering torque on the x-axis. These display the vehicle's reaction to a torque input. A significant dead zone can be observed. This is the region where the curve stretches across the input axis as there is no output in this region. This yields a large deviation from the linear, as indicated in the legend. The steering feedback in the form of torque in relation to steering angle also provides evidence of a dead zone and a large difference from the ideal. The two plots in the middle row of figure 4.25 display the vehicle's reaction to the steering angle input. This is largely unaffected as in the weave test results.

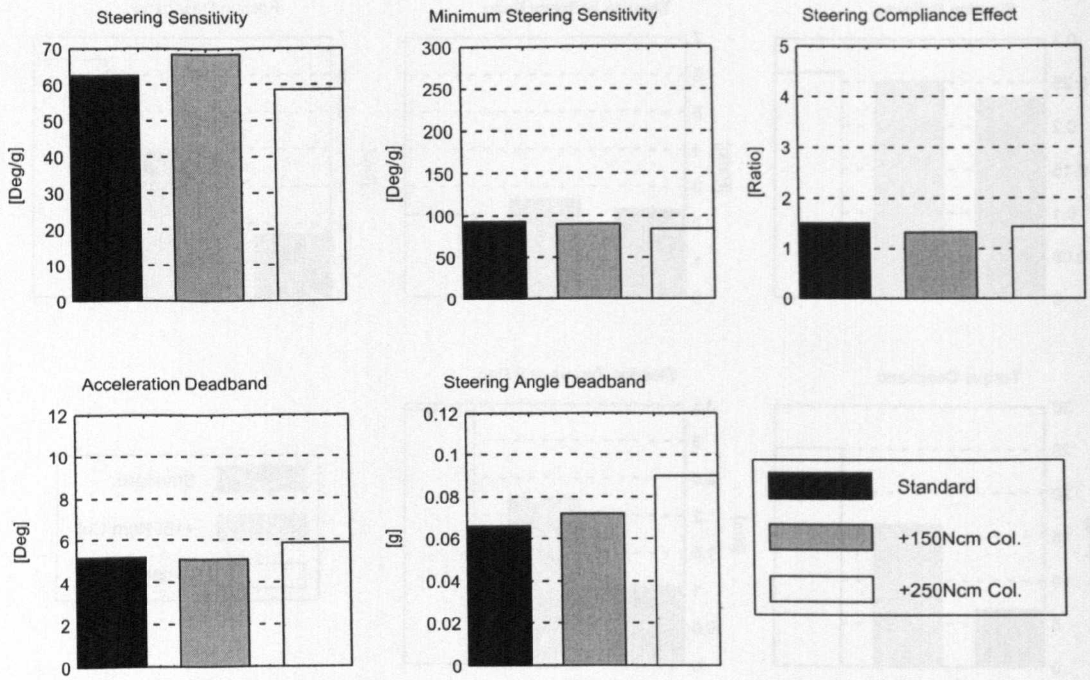

Figure 4.22: Weave test characteristic values - Lateral acceleration vs. Steering wheel angle.

Stationary Circle Test

For the data from the case of added column friction, it is pointless to try to fit a line as there is no visible trend (figure 4.26). The friction covers such a wide range that the steering wheel position can remain fixed, yet the torque can vary in the steering column without overcoming the friction and without affecting the course of the vehicle. The column friction completely disguises the non-linear effects of the tyres, as the level of torque required to overcome the friction is much larger than the levels associated with the torque drop-off. Looking at the data points, the torque becomes more scattered with increased friction until there is no correlation with the vehicle reaction.

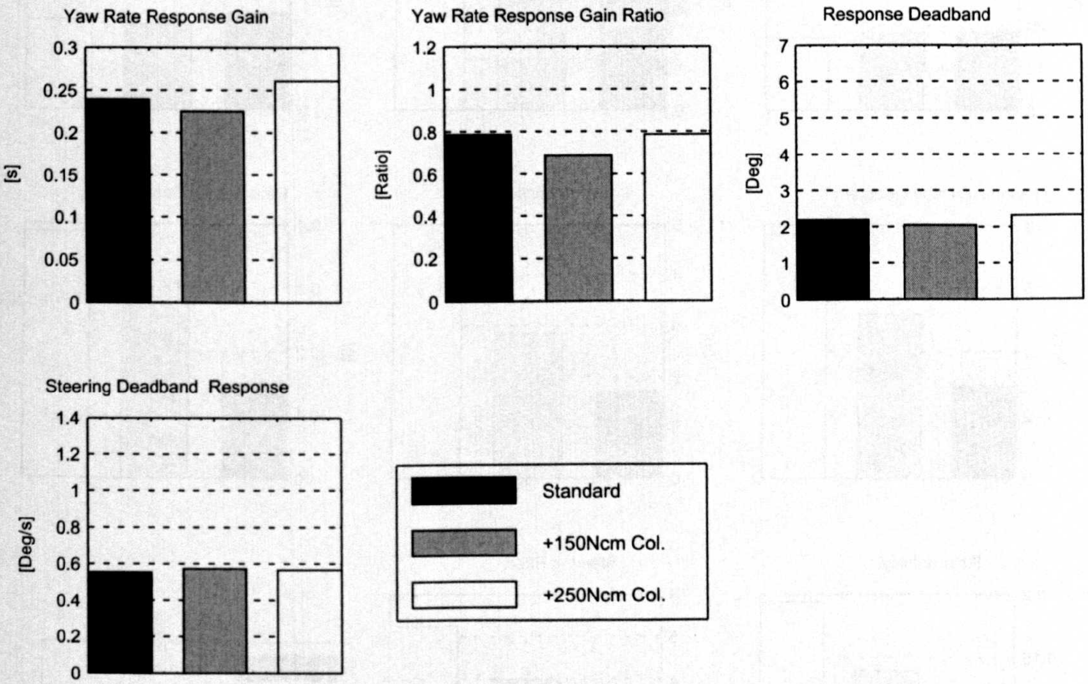

Figure 4.23: Weave test characteristic values - Yaw rate vs. Steering wheel angle.

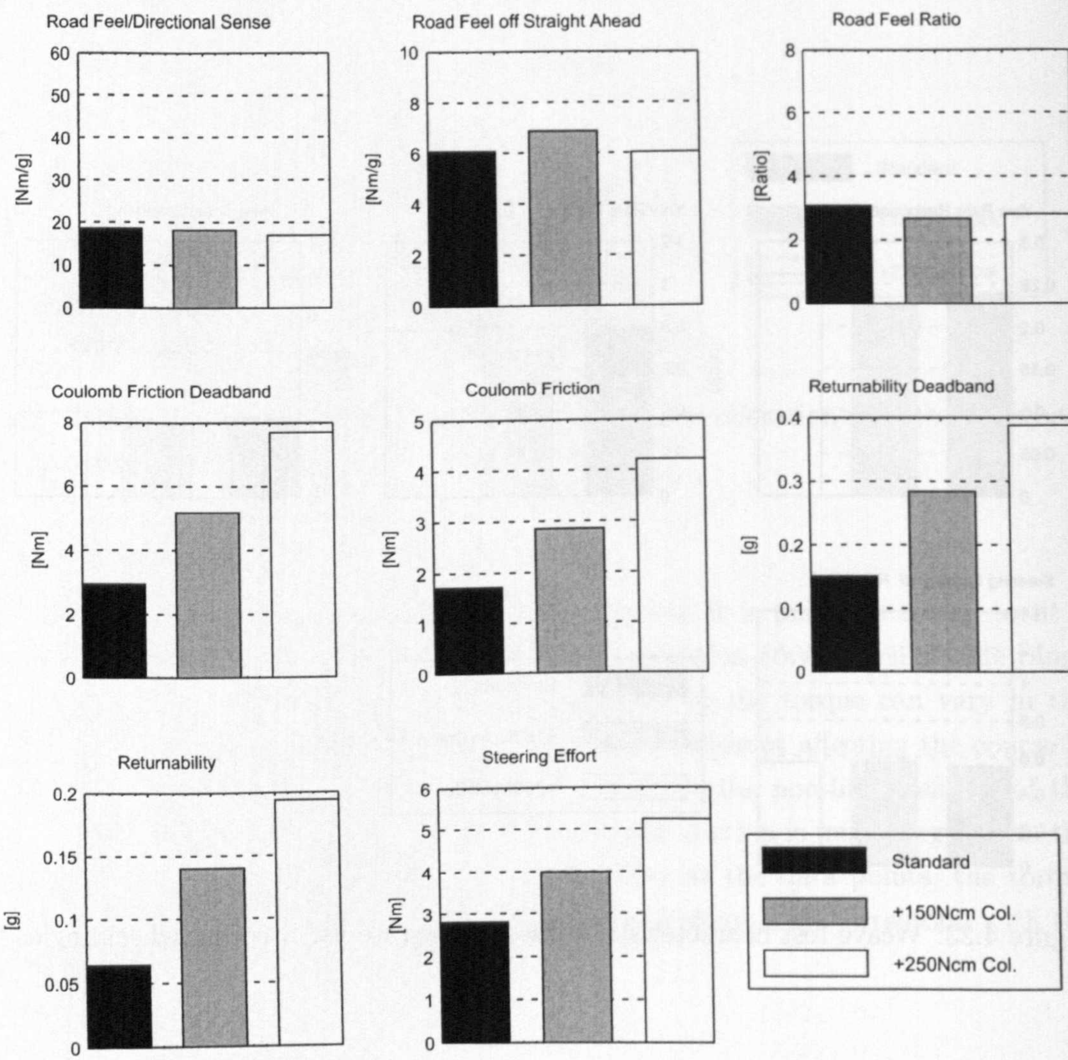

Figure 4.24: Weave test characteristic values - Lateral acceleration vs. Steering torque.

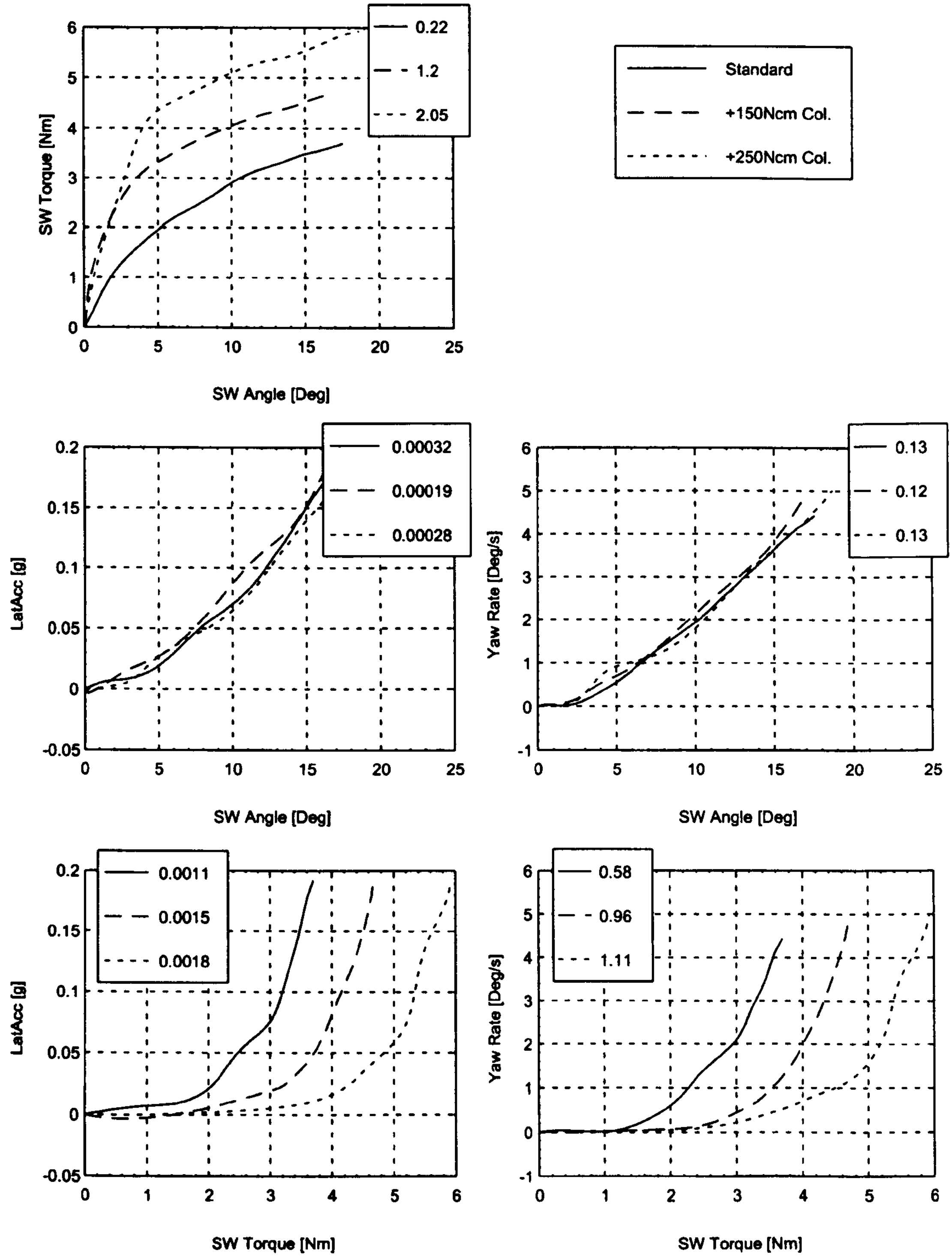

Figure 4.25: Transition test - Figures in legends denote normalised differences from the linear ideal in units of the respective plot's y-axis.

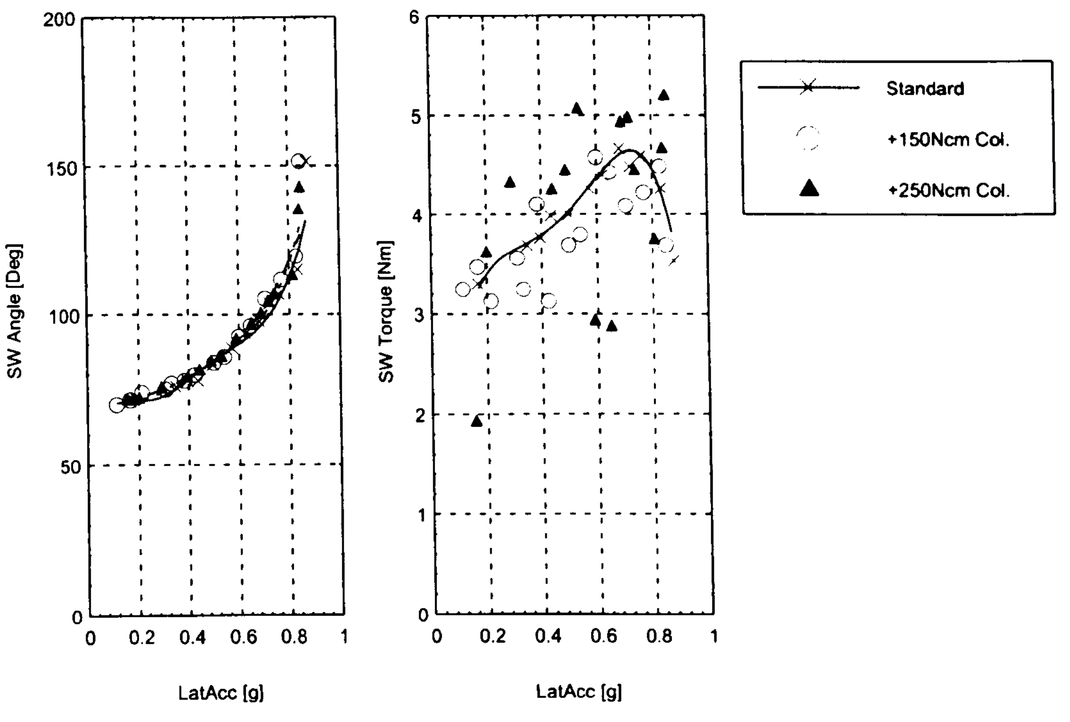

Figure 4.26: Stationary Circle Test - Radius = 40 m. Left.

4.4.3 Effect of Extra Rack Friction

Friction was also added to the steering rack by means of the preloaded yoke described in sections 1.3.1 and 4.3.3. '+500N Rack' labels the variation with the most rack friction and '+380N Rack' is used for an intermediate level.

The Weave Test

The cross plots in figure 4.27 highlight the friction effect by the widening of the hysteresis of the plots involving the steering torque, as was the case with column friction. Similarly, the steering torque vs. angle plot highlights the increase in the overall torque levels uniformly over the range. The friction and torque deadband terms (figure 4.28) reflect the increase in system friction.

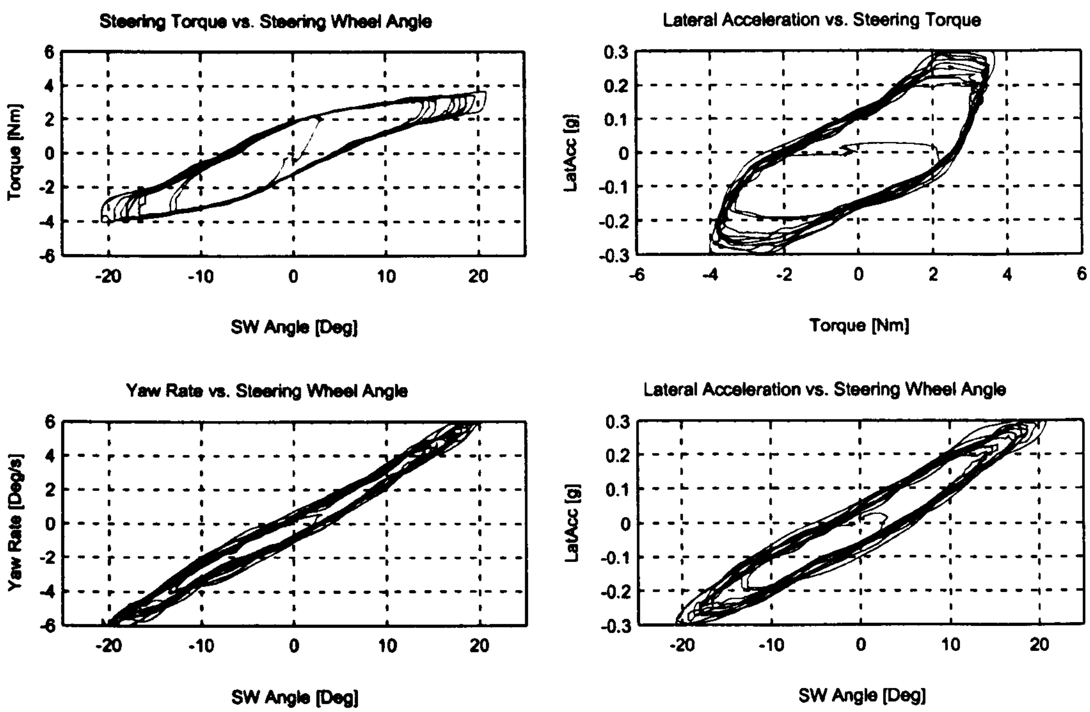

Figure 4.27: Weave test cross plots - **Maximum Rack Friction**.

The rack friction differs from the column friction in its effect on the vehicle response to the steering angle input. The friction occurs on the steering rack, which is separated from the steering input at the wheel by the torsion bar and Hardy disc (section 1.3.1, figure 1.2). Since, there is a larger force to be overcome at the rack, this increases the force in the elastic elements; the Hardy disc and the torsion bar. As a result, these elements deflect more. Therefore, there is added hysteresis between the two bodies, which enlarges the hysteresis between the angle input and the vehicle lateral reaction. This is most evident in the deadbands in figures 4.29 and 4.30.

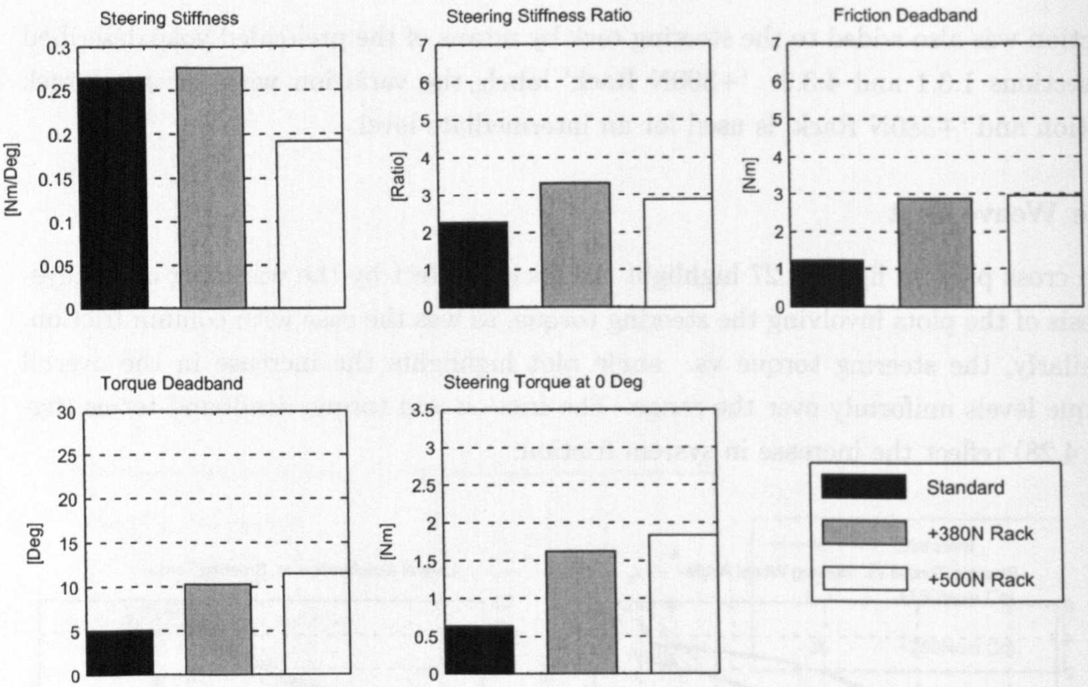

Figure 4.28: Weave test characteristic values - Steering wheel torque vs. Steering wheel angle.

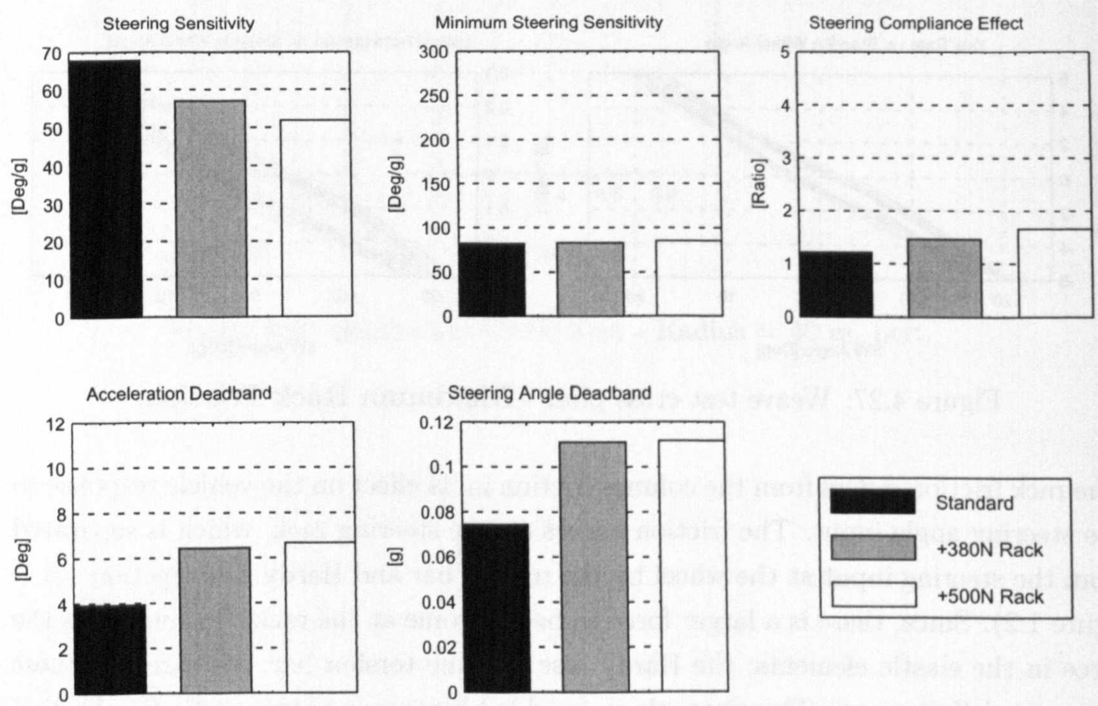

Figure 4.29: Weave test characteristic values - Lateral acceleration vs. Steering wheel angle.

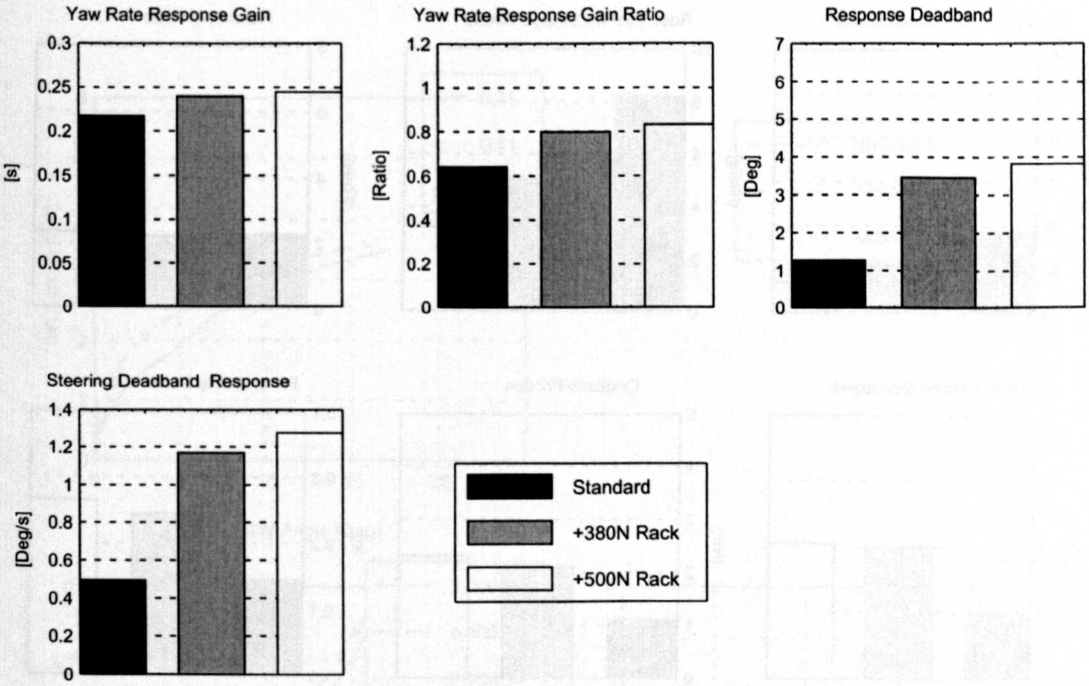

Figure 4.30: Weave test characteristic values - Yaw rate vs. Steering wheel angle.

The larger torque in the torsion bar increases its deflection. This boosts the power assistance, which counteracts the larger friction force to be overcome. Therefore, the effect of an extreme increase in friction is not as large as in the column friction case. Figure 4.31 shows how the deadbands have not reached the same extremes when the friction is on the rack as opposed to the column. However, because the power assistance is active over more of the range due to the higher deflection of the torsion bar, the torque gradient at on-centre and off-centre is affected, as shown by the road feel and road feel off straight ahead terms.

The Transition Test

The friction effect from the alteration to the steering rack produces a similar dead zone in the steering torque/vehicle lateral reaction plots (figure 4.32, third row) as did increasing the column friction. This is reflected in the departure from linearity with added friction, as seen in the plot legends. The secondary effect on the steering angle/vehicle response (second row plots), as described in the rack friction weave test results, is also evident, if only to a small degree, in the transition test. The steering torque vs. steering angle plot is to a lesser extent affected with a dead zone as in the previous friction case, due to the power assistance opposing the friction forces.

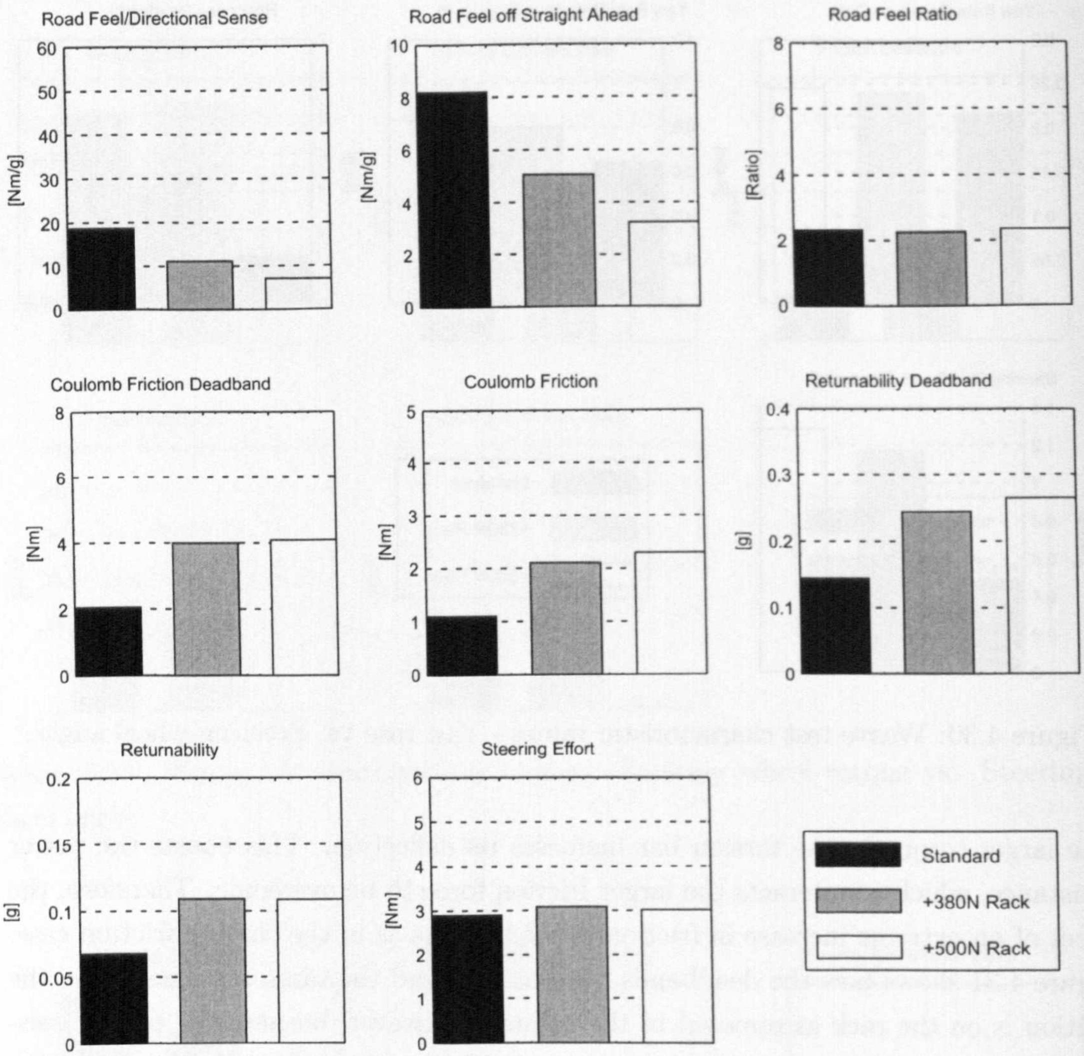

Figure 4.31: Weave test characteristic values - Lateral acceleration vs. Steering torque.

Stationary Circle Test

There is relatively little difference in the torque curve within the rack friction variations (figure 4.33) compared to the column friction variation (4.26). This is due to the power assist, which is boosted as the deflection in the torsion bar increases when overcoming the rack friction. Therefore, the rack friction does not affect the information being communicated from the tyres to the steering wheel and there is no perceived increase in steering torque levels.

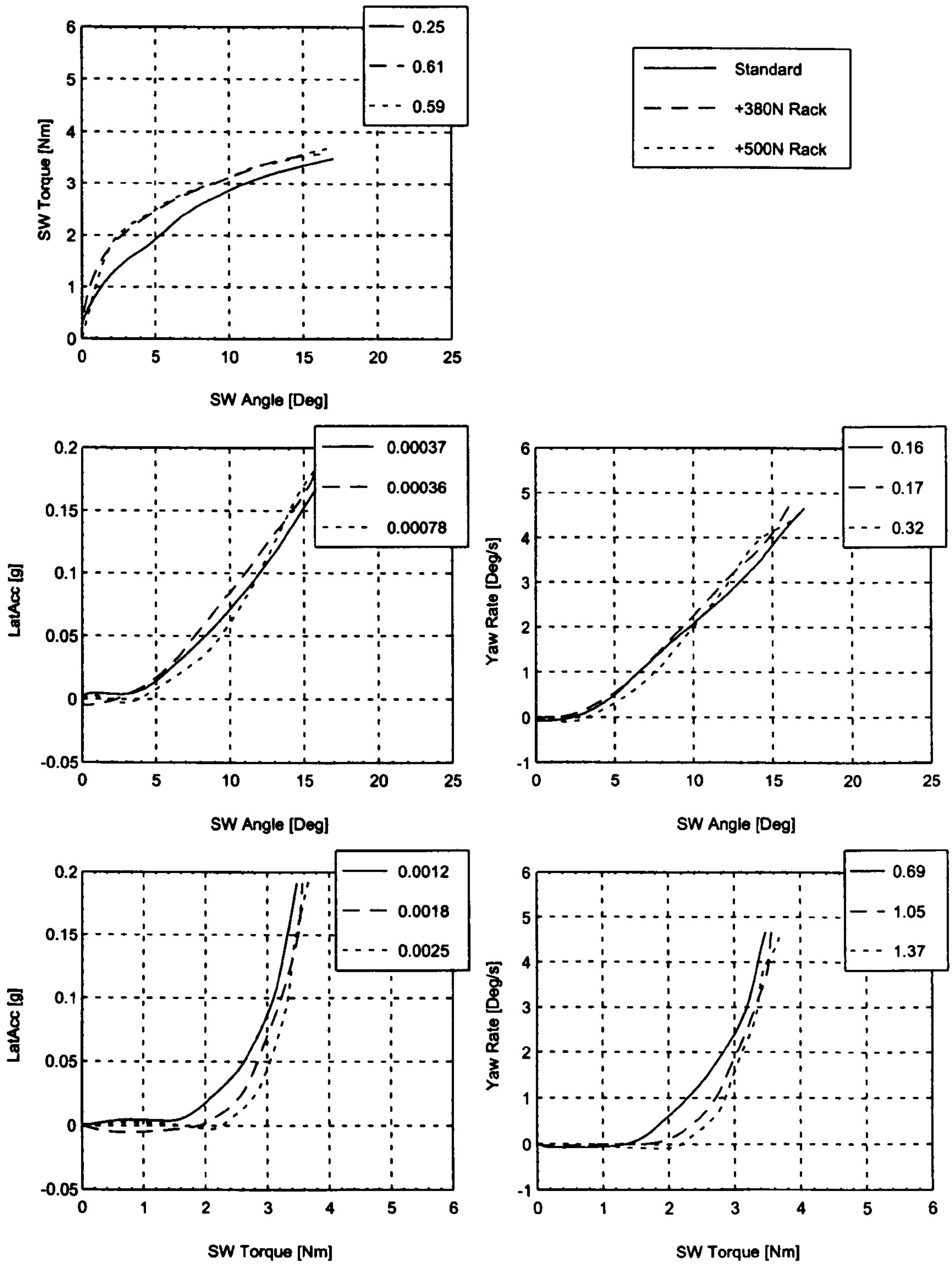

Figure 4.32: Transition test - Figures in legends denote normalised differences from the linear ideal in units of the respective plot's y-axis.

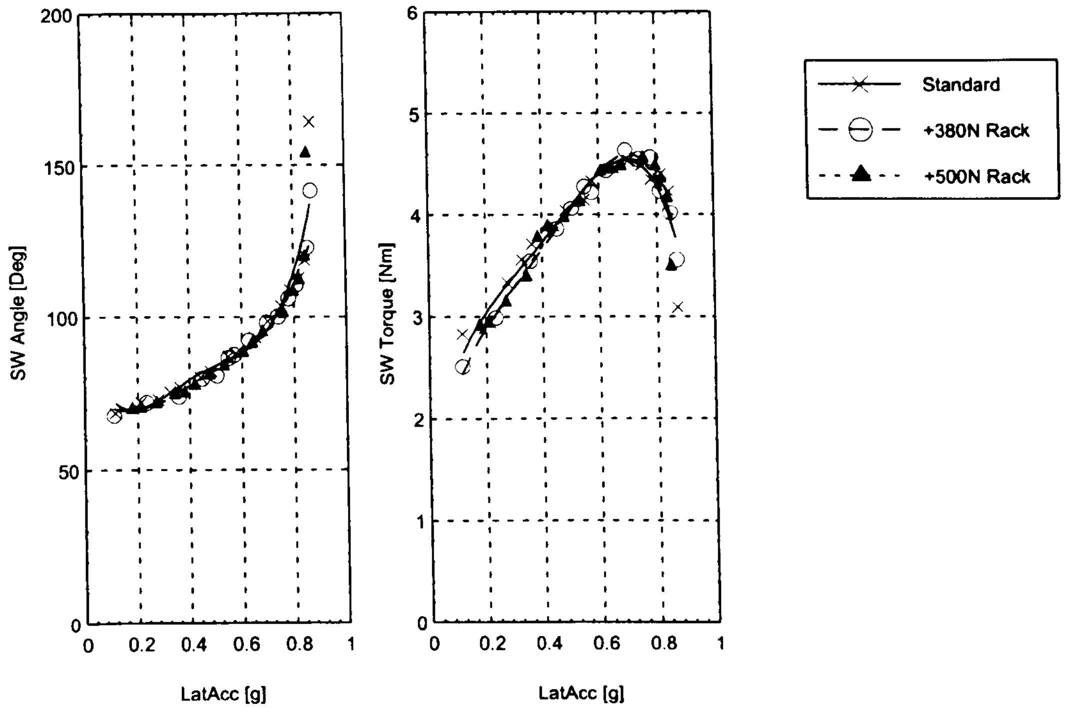

Figure 4.33: Stationary Circle Test - Radius = 40 m, Left.

4.4.4 Effect of Extra Power Assistance

The Servotronic® steering gear was used to provide variable power assistance levels. Tests were carried out with the Servotronic® deactivated, 'Standard', with maximum delivered assistance, '100 % mx PAS', and with half the maximum achievable assistance, '50% mx PAS'. Details of the hydraulic pressure levels to provide the assist are in section 4.3.4.

The Weave Test

The effects of extra power assistance can be clearly seen on first inspection of the cross plots. When the maximum hydraulic force is applied (figure 4.35), the reduction of steering torque is more dramatic compared to the standard hydraulic assistance delivered (figure 4.34).

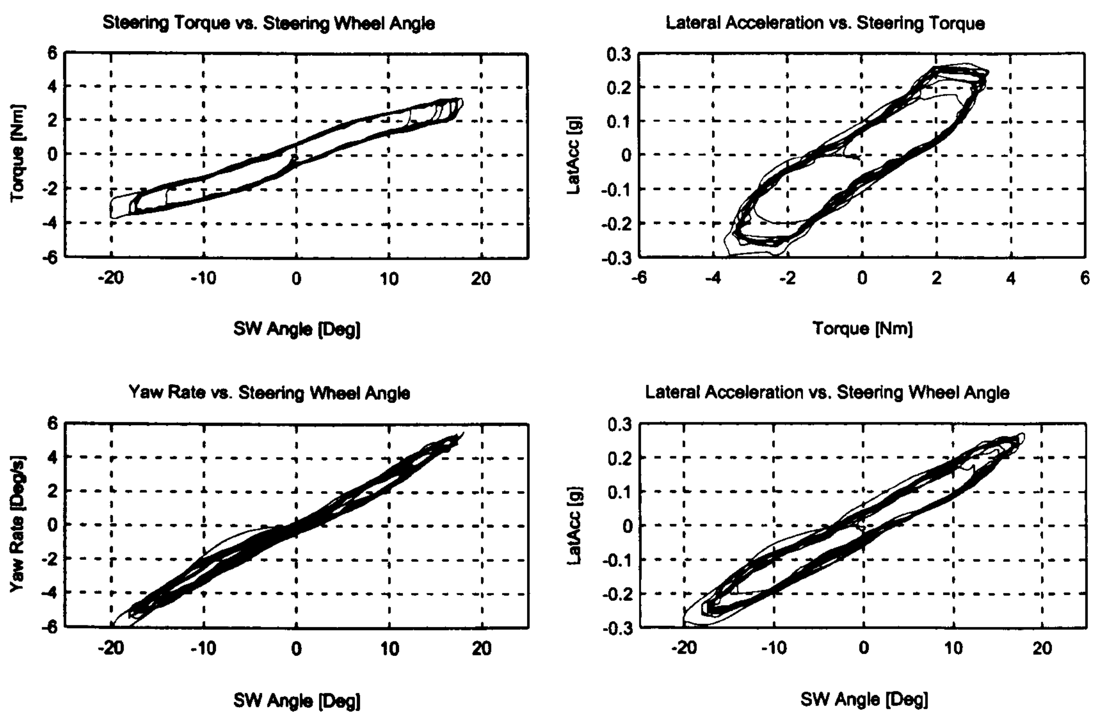

Figure 4.34: Weave test cross plots - Servotronic® Steering Gear - **Standard Assistance.**

The level of assistance has an extreme effect on the steering stiffness ratio term (Figure 4.36), as the steering angle/steering torque relationship is markedly different from on-centre, where there is little hydraulic influence, to the off-centre region, where the hydraulic system is in operation. As the hydraulic system is only activated after a certain torque is built up, the on-centre area is not much affected and the characteristic values on-centre remain similar.

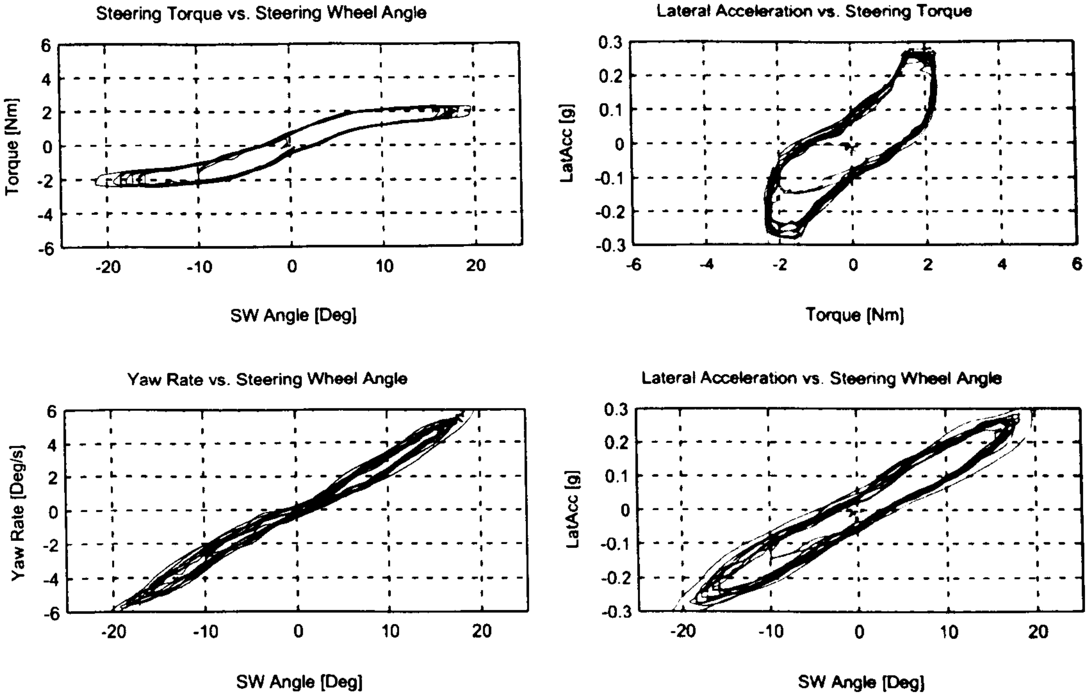

Figure 4.35: Weave test cross plots - Servotronic® - **Maximum Power Assist**.

Since, the power steering system acts only by supplying a supplemental torque, there is no change in the mechanical linkage. Therefore, an applied steering angle will result in a similar road wheel angle despite variation of the power steering torque. As a result, the vehicle reaction to steering wheel angle remains essentially unaffected by this parameter, as can be seen in figures 4.37 and 4.38.

The vehicle reaction to steering torque is remarkably different across this parameter variation. The off-centre behaviour, again, is severely affected and this is depicted by the road feel off straight ahead and the road feel ratio terms in figure 4.39. The steering stiffness ratio and the road feel ratio highlight the non-linearity and discontinuous behaviour from on to off-centre caused by increasing the level of power assistance.

The Transition Test

In this variation, like the column friction in section 4.4.2, the steering torque/vehicle reaction is significantly altered, while the steering angle/vehicle reaction remains little affected. This was encountered previously with the weave test results. However, a slight difference is noted in the yaw rate reaction to the angle input (figure 4.40). It was seen in section 4.4.3, that increased torque levels in the elastic elements in the column create more deflection. In this case, it results in less deflection, due to the decreased torque and thus a more linear response.

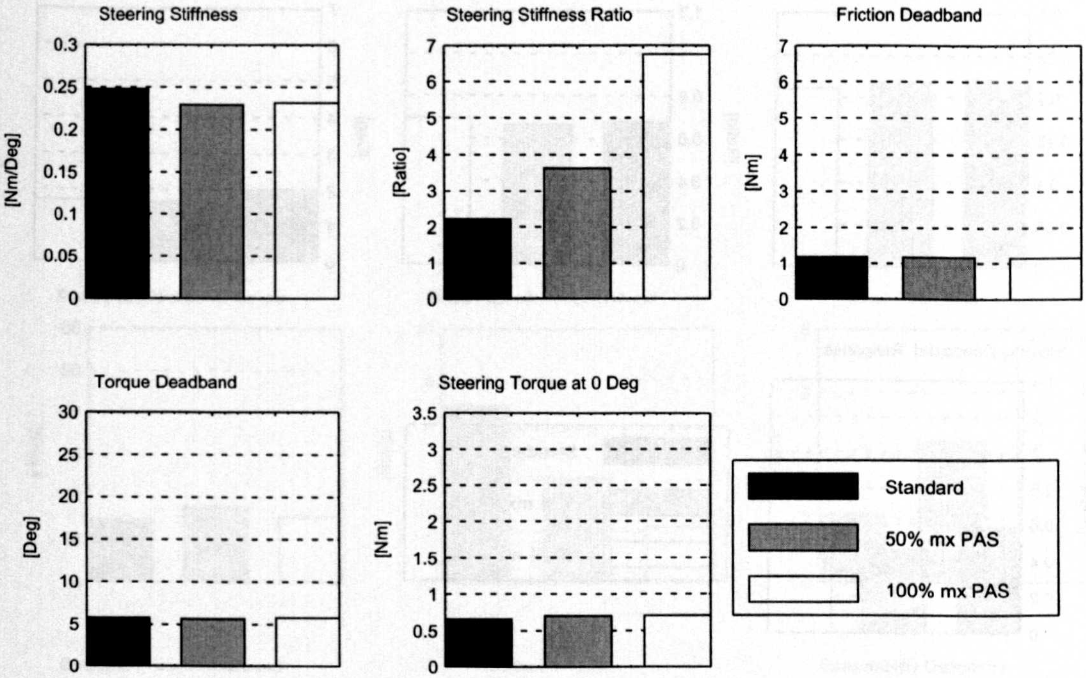

Figure 4.36: Weave test characteristic values - Steering wheel torque vs. Steering wheel angle.

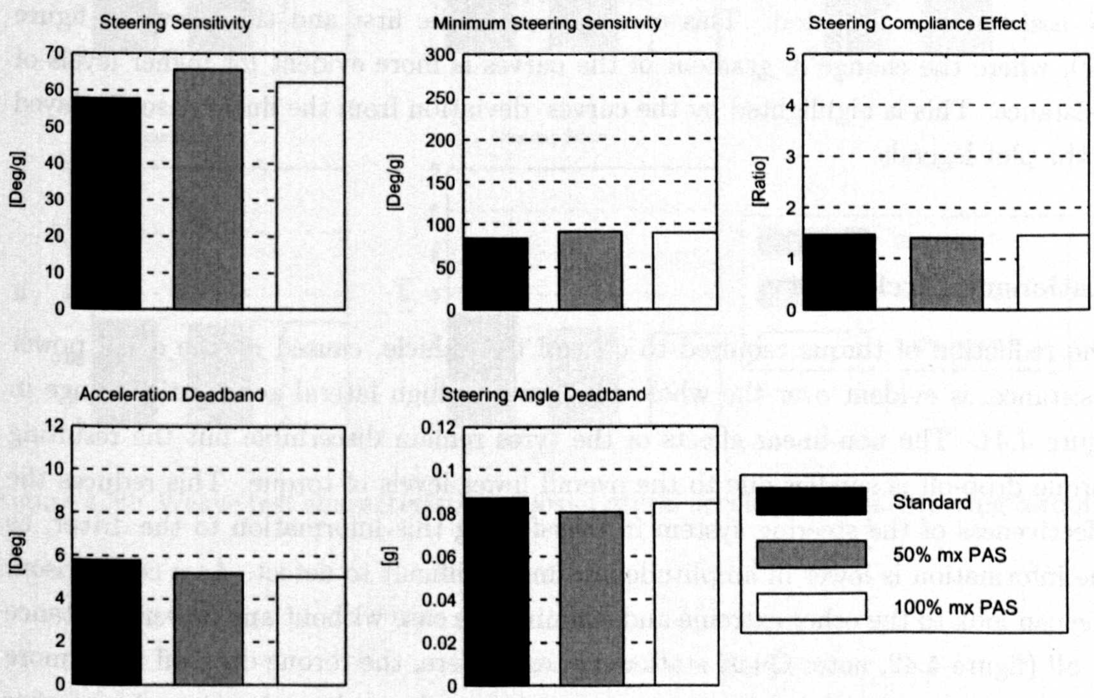

Figure 4.37: Weave test characteristic values - Lateral acceleration vs. Steering wheel angle.

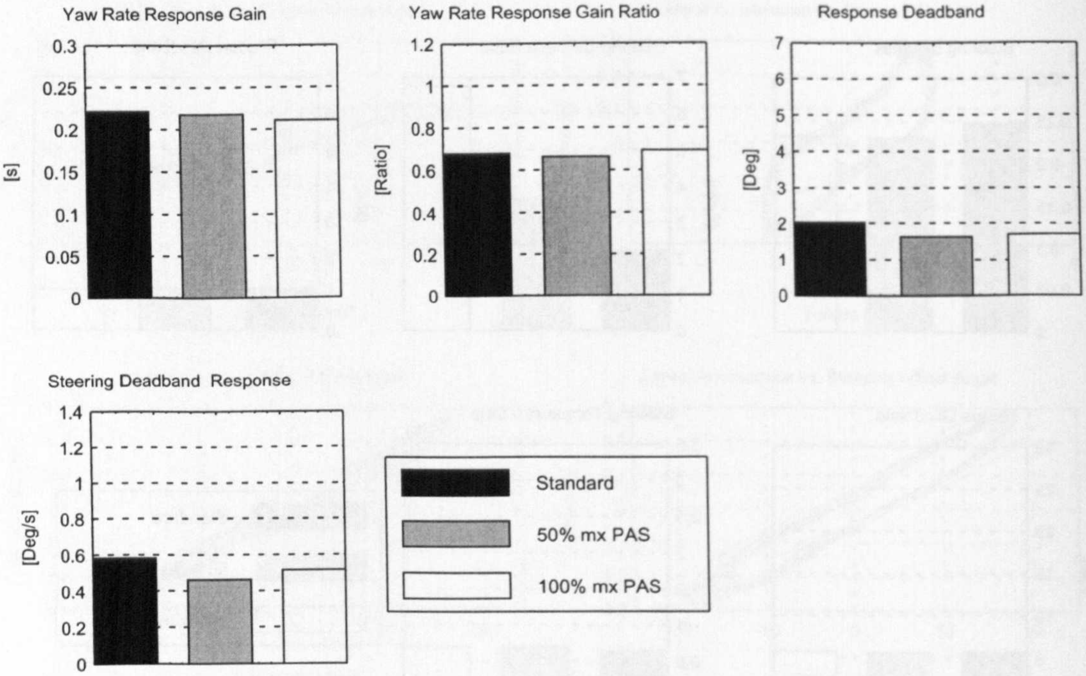

Figure 4.38: Weave test characteristic values - Yaw rate vs. Steering wheel angle.

More obviously, the added power assistance increases the change in behaviour between the areas of operation where the assistance is inactive and the region where the assistance is activated. This can be seen in the first and third rows of figure 4.40, where the change in gradient of the curves is more evident for higher levels of assistance. This is highlighted by the curves' deviation from the linear case displayed in the plot legends.

Stationary Circle Test

The reduction of torque required to control the vehicle, caused by the extra power assistance, is evident over the whole medium and high lateral acceleration range in figure 4.41. The non-linear effects of the tyres remain discernible but the resulting torque drop-off is smaller due to the overall lower levels of torque. This reduces the effectiveness of the steering system in transferring this information to the driver, as the information is lower in amplitude and more difficult to detect. As a comparison, one can look to the other extreme and examine the case without any power assistance at all (figure 4.42, note: Quasi stationary test). Here, the torque drop off is far more dramatic - note the scale of the steering torque vs. Lateral acceleration plot reaches to 20 Nm.

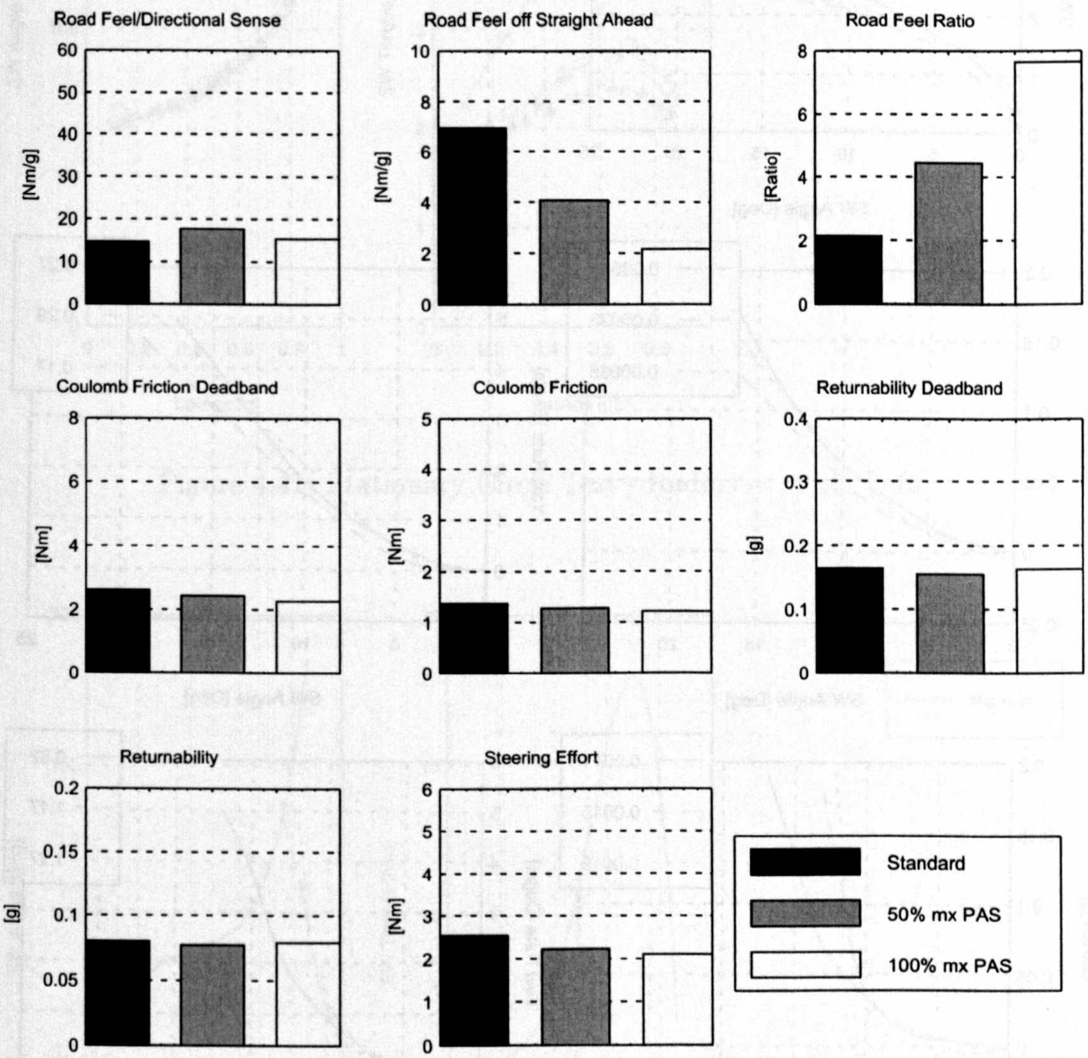

Figure 4.39: Weave test characteristic values - Lateral acceleration vs. Steering torque.

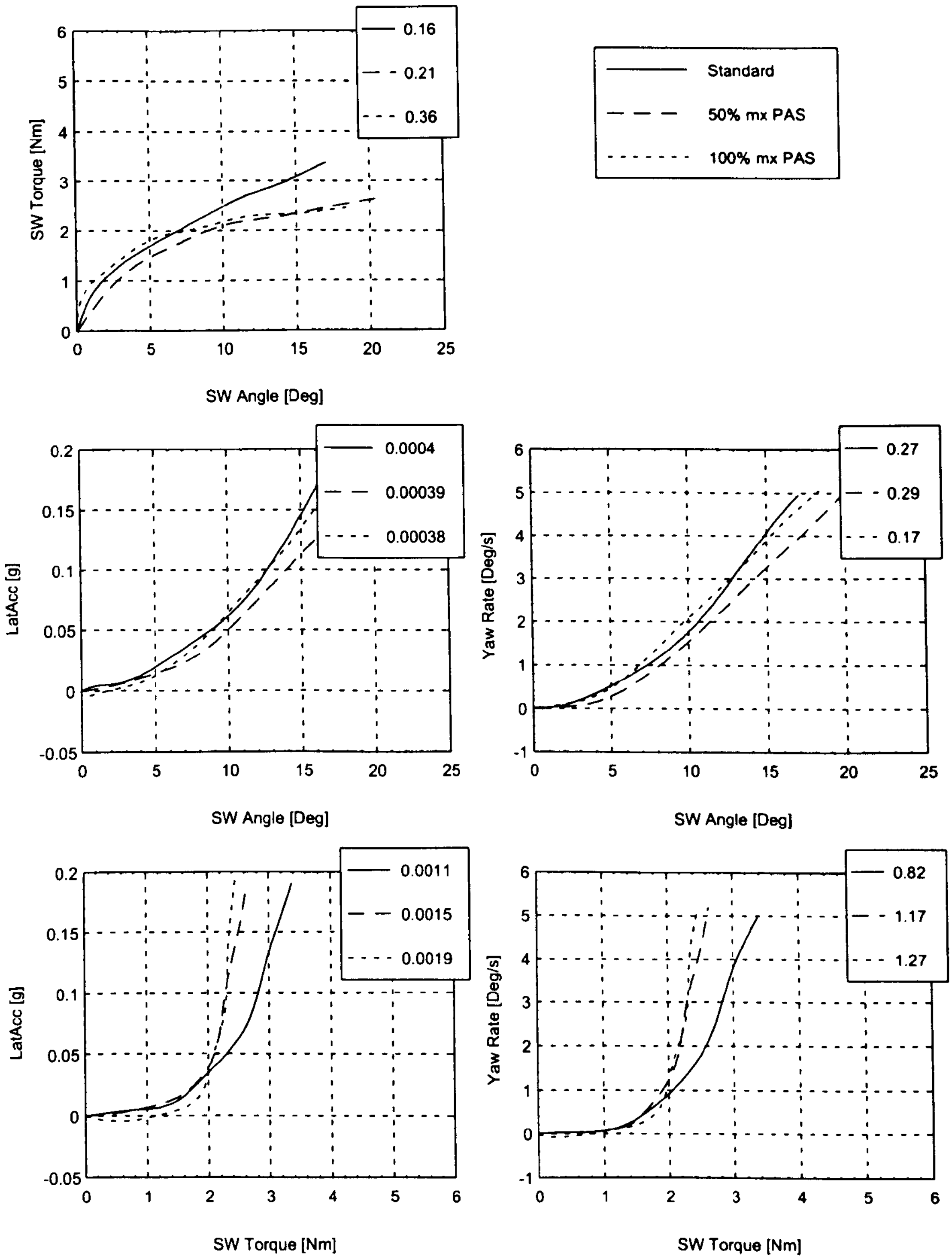

Figure 4.40: Transition test - Figures in legends denote normalised differences from the linear ideal in units of the respective plot's y-axis.

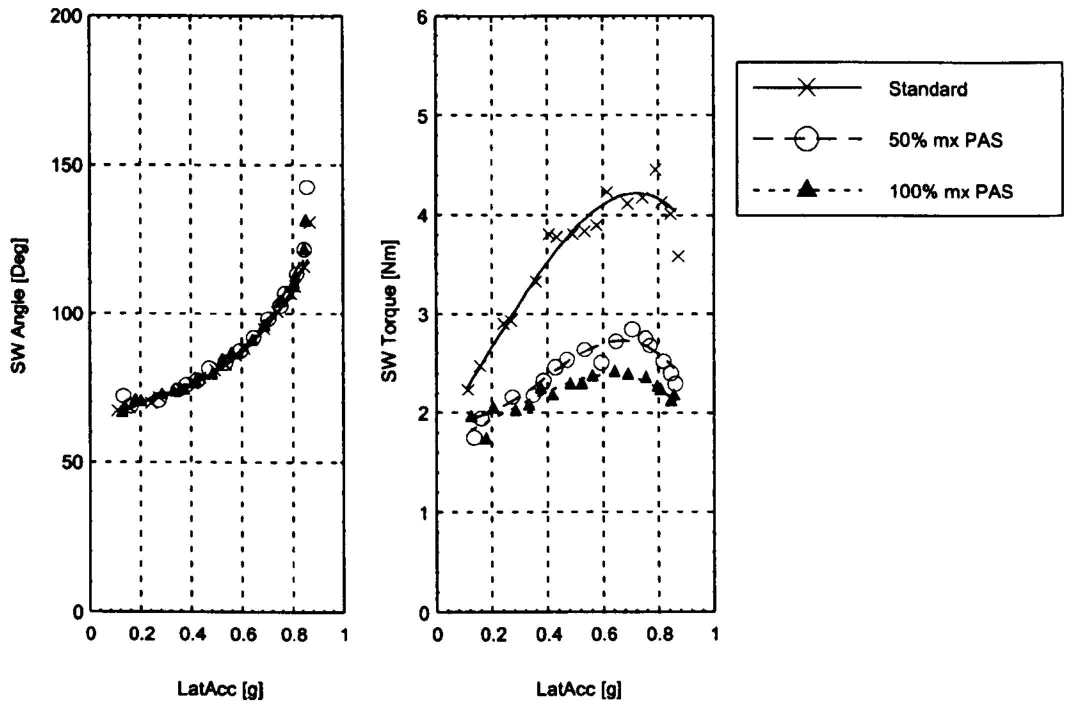

Figure 4.41: Stationary Circle Test - Radius = 40 m, Left.

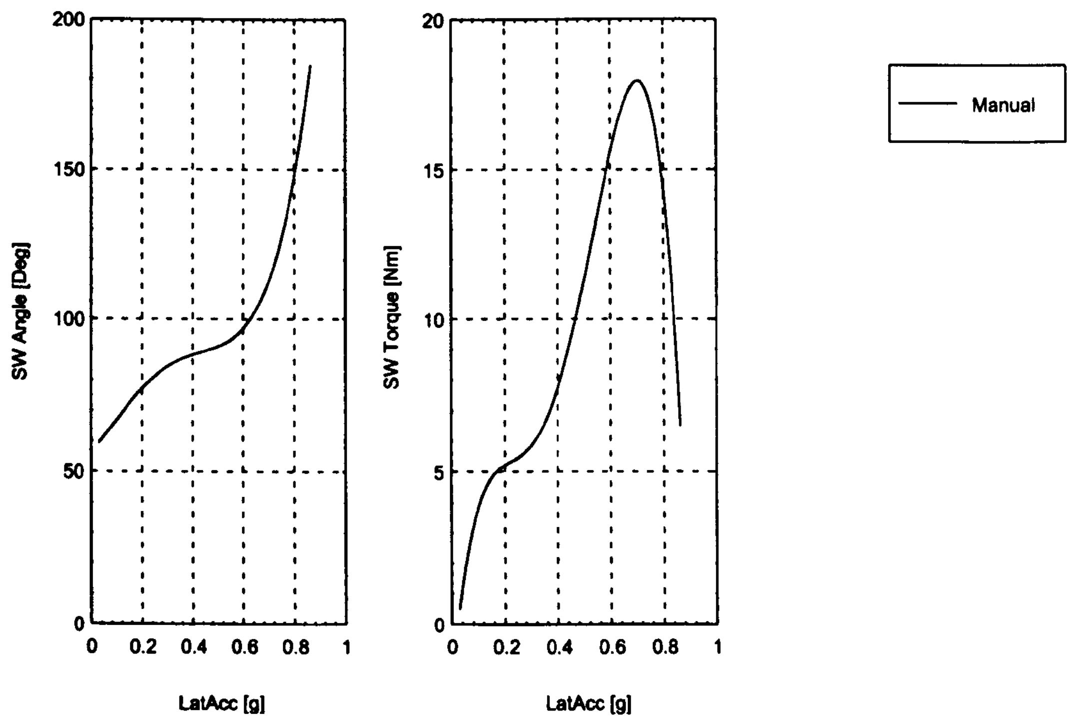

Figure 4.42: QUASI Stationary Circle Test - Radius = 40 m, Left. ZERO Power assistance. (Curve fitted to original data.)

4.4.5 Effect of Extra Free Play

The Weave Test

Free play in the system can be detected by a dead zone where there is no vehicle reaction in the region of the steering angle input where the play is encountered (figure 4.43). As the play is introduced at the zero steering angle position, the on-centre behaviour, and therefore all on-centre characteristics, are affected. The deadbands and on-centre gradients in figures 4.44, 4.45, and 4.46 show this effect for the reaction to the steering angle. Typically the deadbands at zero angle (Friction , steering angle, steering response) are decreased and the reaction deadbands (Torque, Acceleration, Response) are increased (figures 4.44, 4.45, and 4.46 respectively).

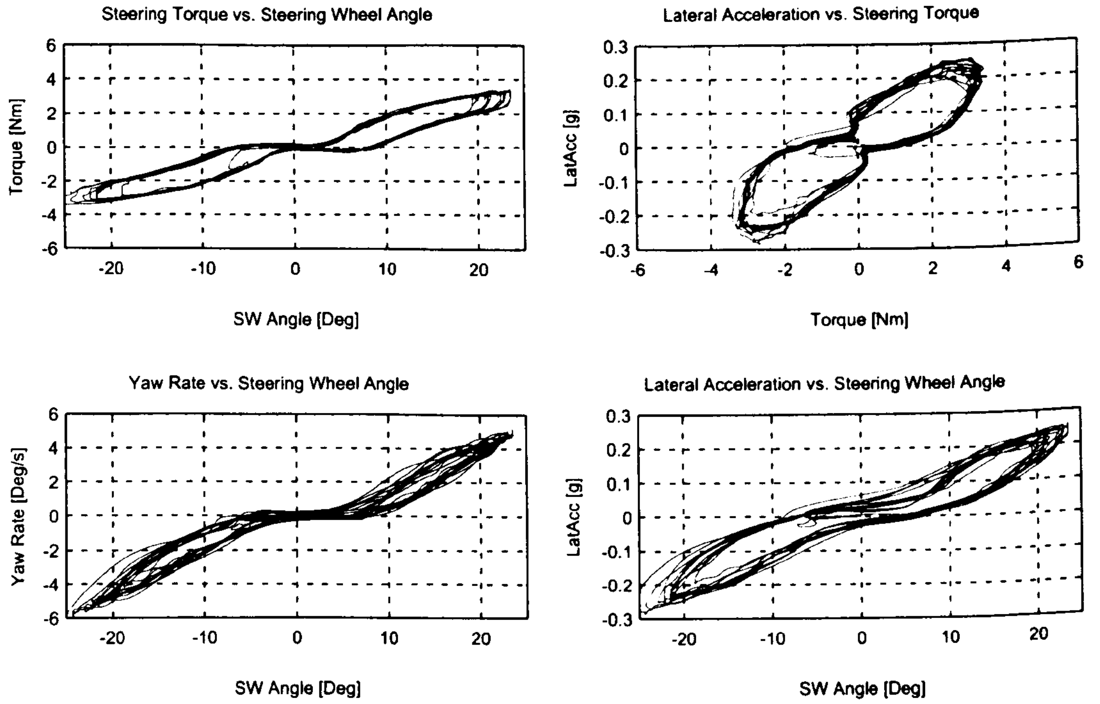

Figure 4.43: Weave test cross plots - **Maximum Play**.

The gradient ratios indicating non-linearity and inconsistency are altered because of the dramatically different on-centre gradients. This is evident upon examination of the steering stiffness, minimum steering sensitivity , road feel, and yaw response gain terms in the respective figures; 4.44, 4.45, 4.47, and 4.46. The respective ratios, however, indicate more continuity rather than less. This is because the slope on-centre, usually steeper, becomes flatter than it is off-centre. There is less of a difference between the gradients and thus the ratio terms are reduced. However, the main feature of the play is to introduce a dead zone, and this is better quantified using the deadbands.

The steering torque/lateral acceleration plot (figure 4.43) is altered differently by the

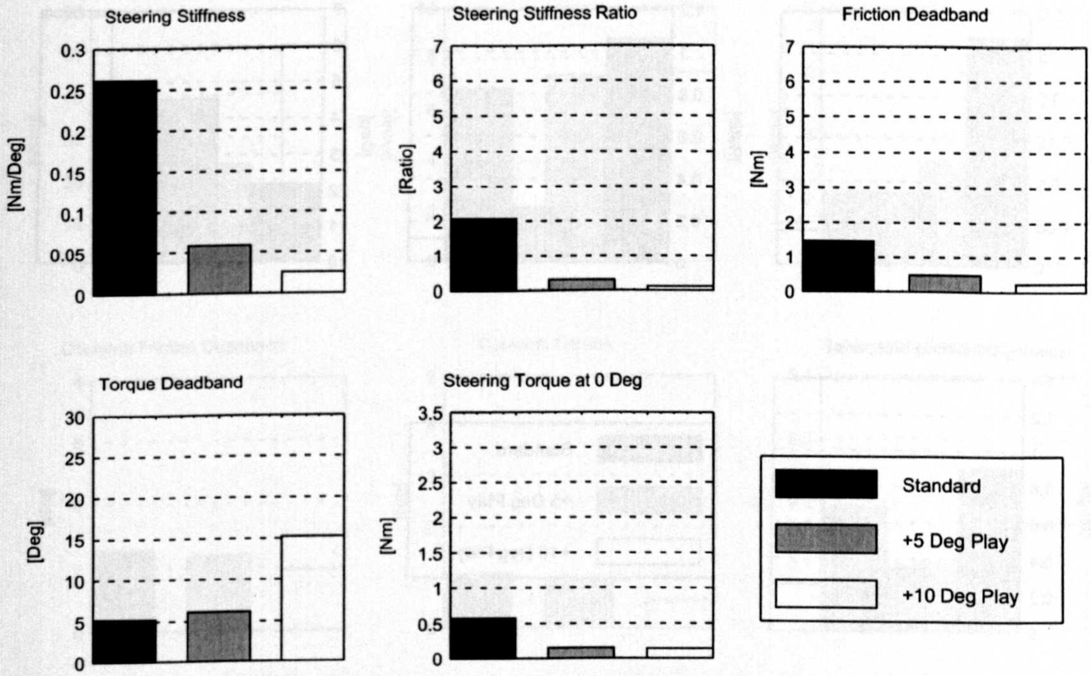

Figure 4.44: Weave test characteristic values - Steering wheel torque vs. Steering wheel angle.

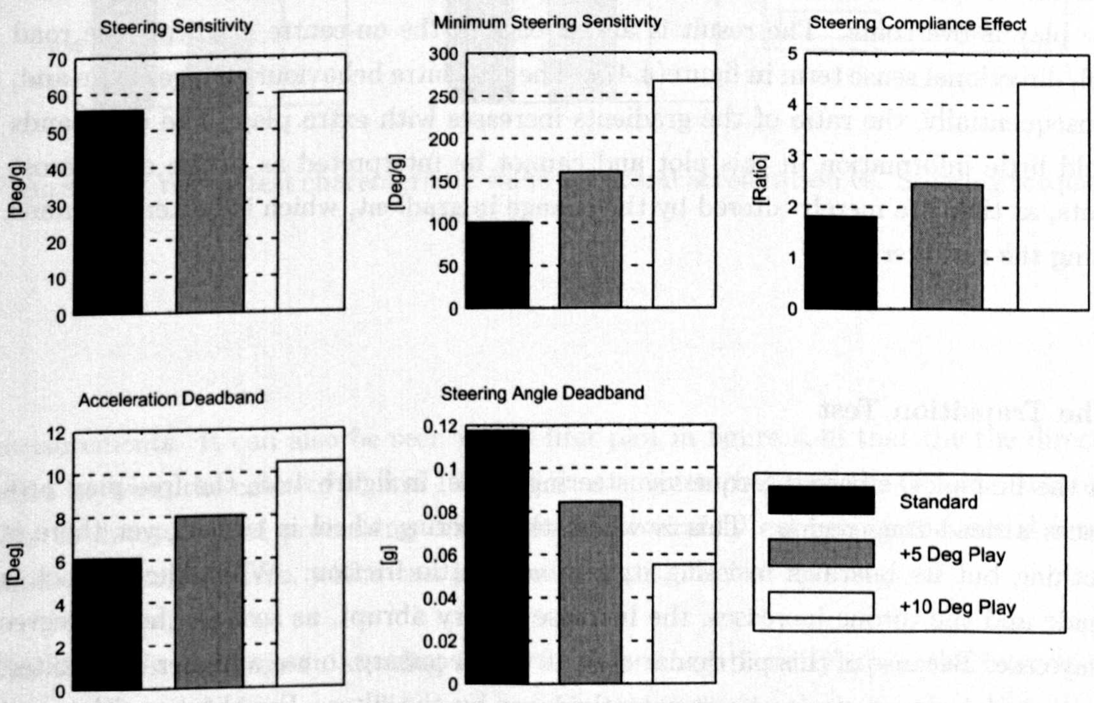

Figure 4.45: Weave test characteristic values - Lateral acceleration vs. Steering wheel angle.

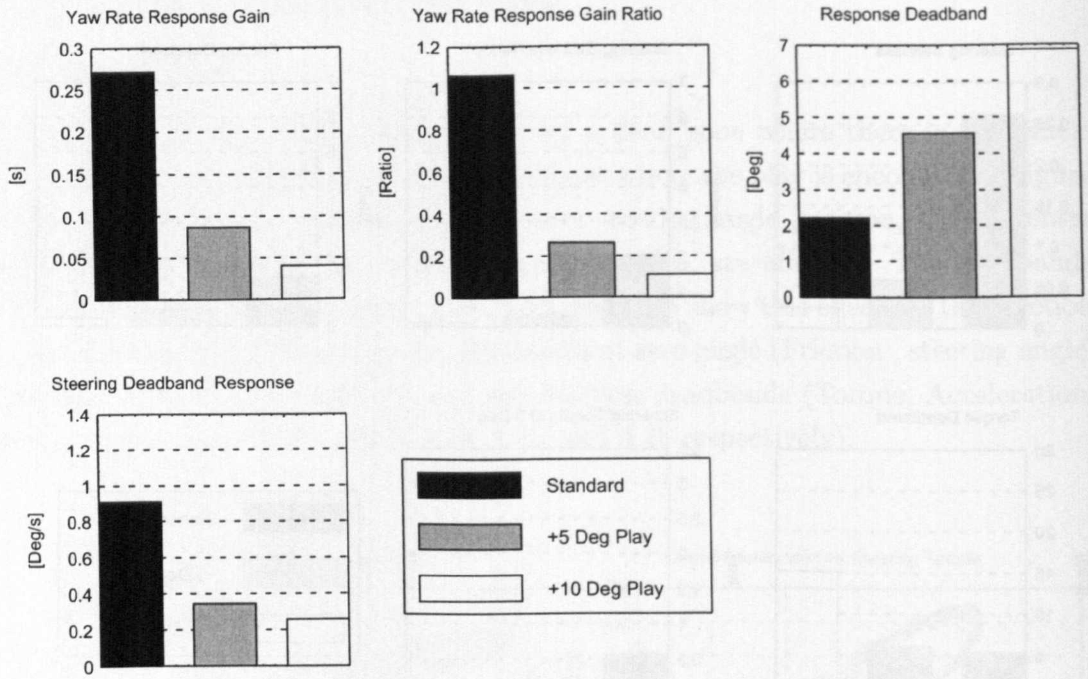

Figure 4.46: Weave test characteristic values - Yaw rate vs. Steering wheel angle.

play in the system. As the torque is increased, the lateral acceleration duly increases. However, upon the change of direction of the steering wheel, the play is encountered and the torque returns to almost zero, as normal, but remains at almost zero until the play is overcome. The result is an increase in the on-centre gradient, the road feel/directional sense term in figure(4.47). The off-centre behaviour changes little and, consequentially, the ratio of the gradients increases with extra play. The deadbands yield little information in this plot and cannot be interpreted as in the other cross plots, as they are merely altered by the change in gradient, which is better examined using the ratio term.

The Transition Test

In the first plot, steering torque vs. steering angle, in figure 4.48, the free play produces a dead zone region. This is where the steering wheel is turned, yet there is nothing but its bearings resisting it, i.e. very little friction. When the contact is made and the torque increases, the increase is very abrupt, as seen in the 10 degree play case. Because of this particular case, it was necessary to use a higher order filter, so that the abruptness was not smoothed out by the filter. For the transition test measurements involving play (figure 4.48 only), the order of the Butterworth zero-phase filter was increased to 20, with the 3dB cutoff point at 15 Hz. The effect of the filter can be seen as the curves are rougher than in the previous transition test

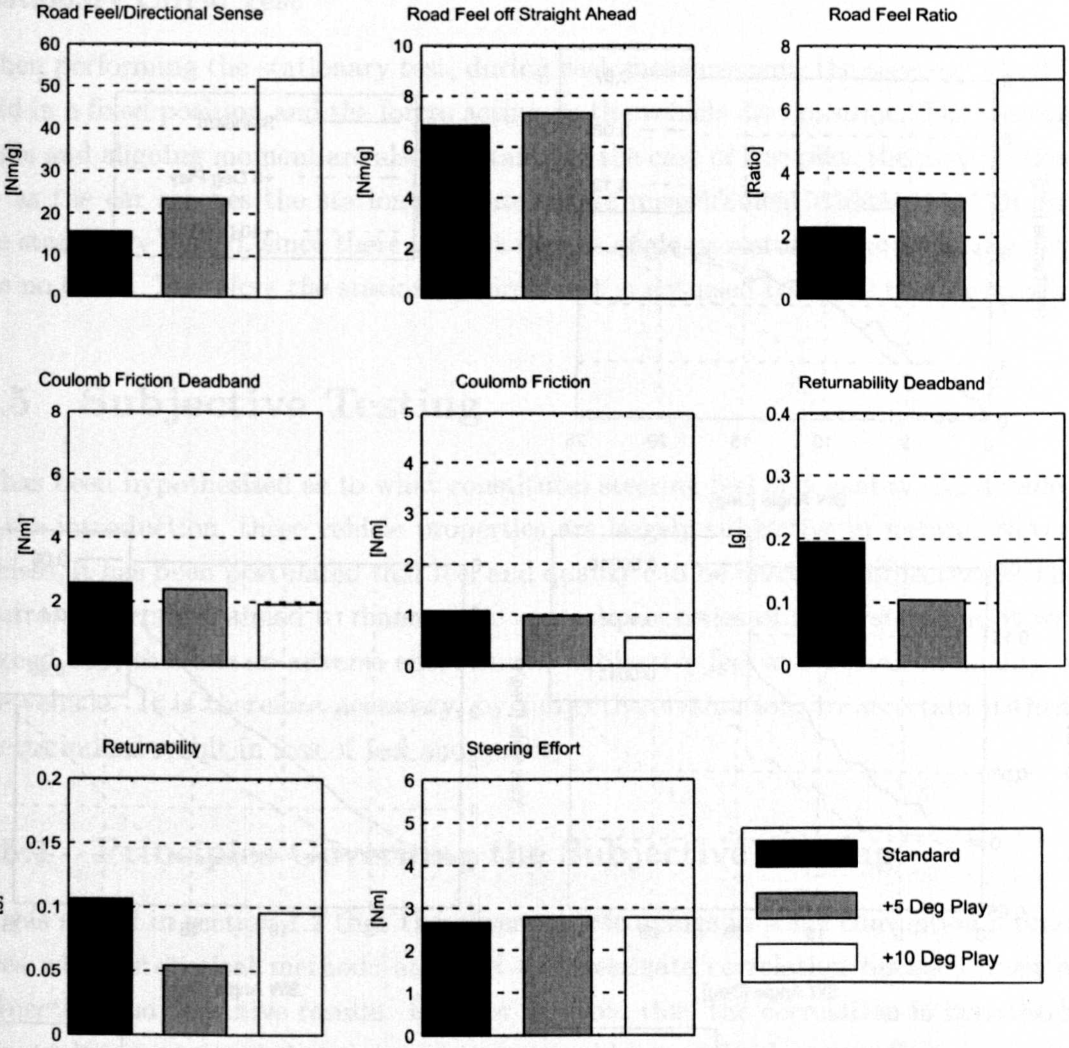

Figure 4.47: Weave test characteristic values - Lateral acceleration vs. Steering torque.

measurements. It can also be seen in the first plot in figure 4.48 that the the direct offset between the cases of 5° and 10° play is not evident between the 0° and 5° cases. This is due to signal processing difficulties in accurately extracting the initial zero point of the manœuvre, which can produce a slight offset of its own.

The vehicle's response to steering input is altered significantly upon the introduction of play to the system. This can be observed most clearly in figure 4.48 in the second row plots. This is similar to the friction case (figure 4.25) except the dead zone for play is in relation to steering angle instead of steering torque. The dead zones are reflected in the deviation from the linear case displayed in the legends.

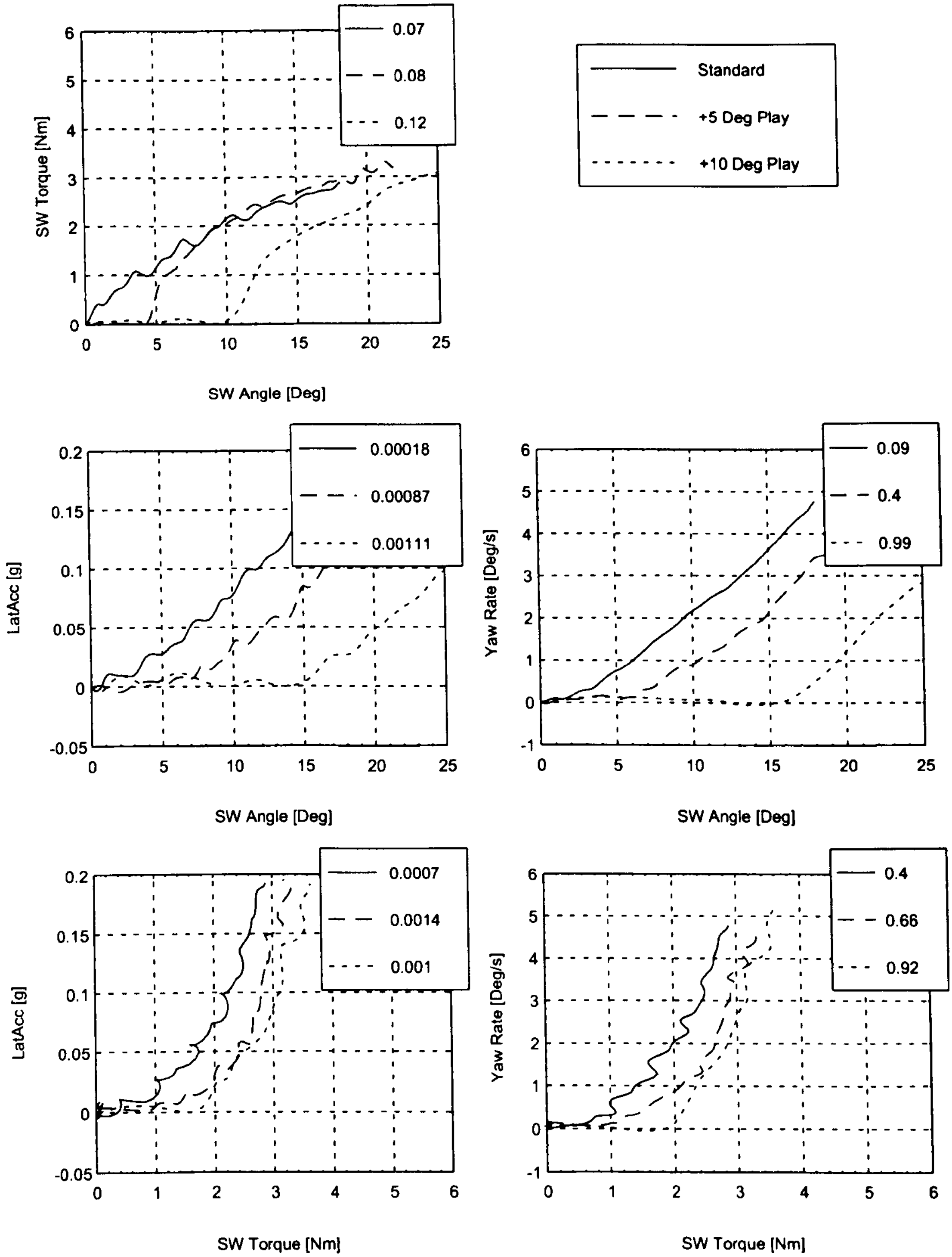

Figure 4.48: Transition test - Figures in legends denote normalised differences from the linear ideal in units of the respective plot's y-axis. Note: Higher order filter used in this variation.

Stationary Circle Test

When performing the stationary test, during each measurement, the steering wheel is held in a fixed position and the forces acting on the vehicle are constant. The steering angle and aligning moment are also constant. In the case of free play, the play is taken up as the car reaches the stationary state before measurement commences. During the stationary period, since there is no change in angle or restoring moment, the play has no effect. Therefore the stationary circle test is not used to assess this variation.

4.5 Subjective Testing

Is has been hypothesised as to what constitutes steering feel and quality. As detailed in the introduction, these vehicle properties are largely subjective in nature. Nevertheless, it has been postulated that feel and quality can be described objectively. The control experiment aimed to damage the control properties of the system and it was argued that this has an adverse effect on the subjective feel and perceived quality of the vehicle. It is therefore necessary, by subjective evaluation, to ascertain if these effects indeed result in loss of feel and quality.

4.5.1 Principles Governing the Subjective Testing

It was stated in section 1.2 that there were shortcomings in some conventional practices where statistical methods are used to investigate correlation between a set of subjective and objective results. In order to avoid this, the correlation is hypothesis driven. It is postulated that the experiment would have a detrimental effect on certain vehicle control properties. With this in mind, the correlation can be more focused on physical mechanisms and does not rely on statistical methods.

As opposed to using a broad spectrum of evaluators in the hope that they form a representative sample of the customer base, it was decided to rely on the assessment of a professional expert evaluator. Gies & Marusic [1998] use experts in a similar manner to provide the link between objective measures, or more loosely, technical features of a vehicle, and the customers' subjective impressions. The expert evaluator's function is not merely to state a preference, but to subjectively compare the assessment of the vehicle to what they know, from experience, to represent quality as perceived by the prospective driver of the car. Crolla et al. [1998] also use experts who are experienced in the field of vehicle dynamics to deliver subjective ratings.

In the experiment, arguably BMW's top subjective evaluator performed the assessment. The evaluator has had over fifteen years experience in vehicle dynamics testing and assessment and can provide consistent subjective evaluations.

4.5.2 Format of Testing

The format of testing and choice of manœuvres were left open to the assessor. Track facilities, including a high speed circuit including 3 km straights, a skid pan, a handling course, and an open vehicle dynamics area, were at the driver's disposal. Thus, there were very few constraints as to how the quality could be assessed and the evaluation methodology was left to the driver's discretion, a principle employed also by Crolla et al. [1998].

As described in the design of experiment (section 4.2.1), only one vehicle parameter was altered at a time. When testing each parameter, the standard configuration was first driven and evaluated before a parameter was varied and another subjective assessment was given. Each assessment lasted about half an hour, although there was no time constraint. The evaluator was equipped with a questionnaire and scored the vehicle during this assessment period.

4.5.3 Questionnaire for Subjective Ratings

Table 4.8 shows the terms used for the subjective evaluation. These were scored, according to the internal BMW subjective rating index, from 1 to 10, with the higher score denoting a better result. The vehicle's reaction to a steering input is described by the agility terms and the amount of steering angle required. The response to a steering torque input and the steering angle/torque relationship are sought after in the feedback and feel terms and the steering wheel torque descriptors. The limit behaviour is investigated by questioning the predictability and safety at the limit with specific terms describing the torque drop-off caused by the tyre saturation.

4.5.4 Subjective Results

The evaluation of the most compliant variation is presented in table 4.9. It is evident that the agility and feedback were judged to decrease with increased compliance. The steering angle required and the torque gradient were deemed to have suffered also and this may contribute to the agility and feedback decreasing.

Table 4.10 yields a result almost directly opposite to that of the compliant variation in table 4.9. The stiffest variation has improved agility and feedback. These suffered with compliance.

When friction is added at the steering column, the subjective result is severely altered (table 4.11). The agility has received a poorer score and the scores for the torque levels and the feedback and feel are significantly reduced with the increase in friction.

Subjective Term		Description	Score
Agility	on-centre	Lethargic/Agile	
	at mid a_y	"	
	at high a_y	"	
Steering wheel angle required	on-centre	Less/More	
	at mid a_y	"	
	at high a_y	"	
Feedback/Steering Feel	on-centre	Insuff./Adequate	
	at mid a_y	"	
	at high a_y	"	
Steering wheel torque	on-centre	Low/High	
	at low a_y	"	
	at high a_y	"	
Steering wheel torque gradient	on-centre	Flat/Steep	
	at low a_y	"	
	at high a_y	"	
Steering wheel torque drop-off	at limit	Less/More	
	progressiveness	Low/High	
	timing	Early/Late	
Predictability near limit	at limit	Low/High	
Safety feel	at limit	Low/High	
Steering - Total Score			

Table 4.8: Subjective terms used in questionnaire. (a_y refers to Lateral acceleration)

The limit behaviour is also adversely affected and the net result is a three point decrease in the overall score.

The rack friction effect is not as great as that of friction at the column. As the rack is assisted by the steering hydraulics, the friction effect is counteracted. Nevertheless, there is a decline in the feedback and agility scores and thus a decrease in the overall subjective rating (table 4.12).

The standard configuration scores for the power assistance variation in table 4.13 are different from those in the previous variation. Unlike the previous experiments, to vary the power assistance the Servotronic® steering rack was employed. This rack, although in principle mechanically identical to the standard rack, differed from it slightly and this is apparent in the subjective score. The relative score denoting the influence of the power assistance is of interest here and therefore, the Servotronic® standard configuration is compared with the Servotronic® configuration with max-

Subjective Term		Standard	Compliant
Agility	on-centre	8	6
	at mid a_y	7	6
	at high a_y	8	6
Steering wheel angle required	on-centre	8	6
	at mid a_y	8	6
	at high a_y	7	7
Feedback/Steering Feel	on-centre	8	5
	at mid a_y	8	7
	at high a_y	8	6
Steering wheel torque	on-centre	8	8
	at low a_y	8	8
	at high a_y	8	8
Steering wheel torque gradient	on-centre	8	6
	at low a_y	7	6
	at high a_y	8	7
Steering wheel torque drop-off	at limit	7	8
	progressiveness	8	8
	timing	8	8
Predictability near limit	at limit	8	8
Safety feel	at limit	8	7
Steering - Total Score		8	7

Table 4.9: Compliance variation - Most compliant. Subjective result

imum assistance. It can be seen from table 4.13 that the feedback and the limit behaviour have suffered as a result of the increase in hydraulic assistance. This is then reflected in the total score, which also worsens.

The standard scores for the subjective evaluation of the play effect also differ from the other standard configuration scores. Due to logistical constraints, the original test car was unavailable for the subjective evaluation of the play variation. A similar test vehicle was employed for this single test and the subjective result is, as a result, slightly dissimilar. It is the relative score which is of most relevance and this is obtained from the result. Table 4.14 presents the subjective evaluation for this configuration and it is evident that the clearance in the column has caused a severe alteration in the evaluator's judgement of the vehicle quality. The evaluator (according to annotations on the questionnaire) noticed the inconsistency and lack of progression in the torque gradient and agility terms, which received very poor scores with the increased play. The on-centre region, where the clearance is encountered, has suffered most subjectively

Subjective Term		Standard	Stiff
Agility	on-centre	8	9
	at mid a_y	7	8
	at high a_y	8	9
Steering wheel angle required	on-centre	8	8
	at mid a_y	8	8
	at high a_y	7	7
Feedback/Steering Feel	on-centre	8	9
	at mid a_y	8	9
	at high a_y	8	9
Steering wheel torque	on-centre	8	8
	at low a_y	8	8
	at high a_y	8	8
Steering wheel torque gradient	on-centre	8	9
	at low a_y	7	8
	at high a_y	8	8
Steering wheel torque drop-off	at limit	7	8
	progressiveness	8	8
	timing	8	7
Predictability near limit	at limit	8	8
Safety feel	at limit	8	9
Steering - Total Score		8	9.5

Table 4.10: Compliance variation - Stiffest. Subjective result

and the overall score is very low.

Subjective Term		Standard	Col. Friction
Agility	on-centre	8	5
	at mid a_y	7	6
	at high a_y	8	6
Steering wheel angle required	on-centre	8	7
	at mid a_y	8	8
	at high a_y	7	8
Feedback/Steering Feel	on-centre	8	3
	at mid a_y	8	5
	at high a_y	8	6
Steering wheel torque	on-centre	8	4
	at low a_y	8	5
	at high a_y	8	6
Steering wheel torque gradient	on-centre	8	5
	at low a_y	7	6
	at high a_y	8	6
Steering wheel torque drop-off	at limit	7	6
	progressiveness	8	7
	timing	8	6
Predictability near limit	at limit	8	6
Safety feel	at limit	8	5
Steering - Total Score		8	5

Table 4.11: Column friction variation. Subjective result

Subjective Term		Standard	Rack Friction
Agility	on-centre	8	5
	at mid a_y	7	7
	at high a_y	8	6
Steering wheel angle required	on-centre	8	7
	at mid a_y	8	8
	at high a_y	7	7
Feedback/Steering Feel	on-centre	8	5
	at mid a_y	8	7
	at high a_y	8	8
Steering wheel torque	on-centre	8	6
	at low a_y	8	6
	at high a_y	8	7
Steering wheel torque gradient	on-centre	8	6
	at low a_y	7	6
	at high a_y	8	7
Steering wheel torque drop-off	at limit	7	7
	progressiveness	8	8
	timing	8	8
Predictability near limit	at limit	8	8
Safety feel	at limit	8	8
Steering - Total Score		8	6

Table 4.12: Rack friction variation. Subjective result

Subjective Term		Standard	Max Assist
Agility	on-centre	6	7
	at mid a_y	7	8
	at high a_y	6	7
Steering wheel angle required	on-centre	7	7
	at mid a_y	7	7
	at high a_y	8	8
Feedback/Steering Feel	on-centre	8	7
	at mid a_y	8	6
	at high a_y	8	5
Steering wheel torque	on-centre	7	7
	at low a_y	8	7
	at high a_y	7	3
Steering wheel torque gradient	on-centre	8	8
	at low a_y	7	8
	at high a_y	7	4
Steering wheel torque drop-off	at limit	8	5
	progressiveness		
	timing		
Predictability near limit	at limit	8	5
Safety feel	at limit	8	5
Steering - Total Score		7	5

Table 4.13: Power assistance variation. Subjective result

Subjective Term		Standard	Play
Agility	on-centre	8	4
	at mid a_y	7	5
	at high a_y	8	6
Steering wheel angle required	on-centre	8	5
	at mid a_y	8	8
	at high a_y	7	7
Feedback/Steering Feel	on-centre	7	1
	at mid a_y	7	5
	at high a_y	8	6
Steering wheel torque	on-centre	7	7
	at low a_y	9	9
	at high a_y	7	7
Steering wheel torque gradient	on-centre	7	5
	at low a_y	6	5
	at high a_y	7	5
Steering wheel torque drop-off	at limit	7	7
	progressiveness	7	7
	timing	8	8
Predictability near limit	at limit	8	8
Safety feel	at limit	8	7
Steering - Total Score		7	2

Table 4.14: Free play variation. Subjective result

Chapter 5

Simulation

5.1 Introduction

5.1.1 The Need for Simulation

Simulation is now commonplace in vehicle development. It provides a method for the prediction of vehicle properties without the high cost associated with hardware testing. It is also a powerful analysis tool used to gain more knowledge about how a system functions and can be used for detailed analysis with less time and effort than conventional testing. Modelling is the definition of a series of relationships between the system parameters and variables that predict a system's behaviour. Therefore, a simulation can only be carried out successfully if the relationships governing the system are known (apart from self learning programs). That implies the modeller must understand how the vehicle parameters affect the vehicle's behaviour. In the process of creating a simulation, a good understanding of the system must be present and this is developed until the modeller can correctly represent the vehicle's behaviour.

5.1.2 Simulation Method

The focus of the analysis is on how the steering system affects quality. Thus, the focus of modelling is on the steering system as opposed to the entire vehicle. Nonetheless, a vehicle model and a tyre model are required as the entire vehicle is used as a platform for the testing. So, the requirements for a vehicle model are:

- Accurate representation of the vehicle's responses for the test manœuvres.
- The provision of a platform for the addition of a steering model.
- The capability of the inclusion of tyre properties.
- Maximum simplicity with respect to ease of computation.

Taking these requirements into consideration it was decided to represent the vehicle by a single track or bicycle model. A single track model uses certain assumptions, which mean that both wheels of an axle can be treated as one, and thus the vehicle is modelled with two wheels on a single track. This reduces the complexity by reducing the degrees of freedom and computational variables. This will be described fully in section 5.2.1. The single track approach is extensively used in the motor industry. Dettki [1997] and Loth [1997] use it when modelling straight ahead running while Smakman [2000] and Schaible [1998] include it in their studies of chassis control systems and side wind sensitivity respectively.

The standard bicycle model does not contain a model of the vehicle's steering system. It allows only the direct input of the front wheel steer angle. In order to model the steering system a separate model was constructed and then appended to the single track model as in section 5.2.2.

The addition of more detailed tyre modelling was also required, as the manoeuvres outlined in section 4.2.4 venture into the non-linear operational area of tyre behaviour. The addition of this tyre model is done via a characteristic curve produced by a larger, more complicated vehicle model detailed in section 5.2.3.

A similar approach to this was taken by Post [1995] when modelling on-centre handling.

5.2 Modelling

5.2.1 Vehicle Model

The vehicle model chosen was the single track vehicle model or bicycle model. This model was first documented by Riekert & Schunck [1940] and has been reported by Mitschke [1990]. The model reduces the two tracks of a two axle vehicle to a single track by assuming that the centre of gravity of the vehicle lies on the road surface. Therefore, there is no weight transfer from the inner to outer tracks and no rolling of the chassis. A second assumption is made at this stage: The tyre side force is proportional to the side-slip angle i.e. linear tyre behaviour. (When incorporating the tyre model in section 5.2.3, this assumption will no longer be valid and will be dealt with then.) The model is depicted in figure 5.1 with the kinematic quantities and figure 5.2 with the forces .

Equations of Motion for the Single Track Model

The equilibrium equation for the forces perpendicular to the Longitudinal Axis:

$$m\,a_y - F_{yR} + F_{Wy} - F_{xF}\,sin\,\delta_F - F_{yF}\,cos\,\delta_F = 0 \tag{5.1}$$

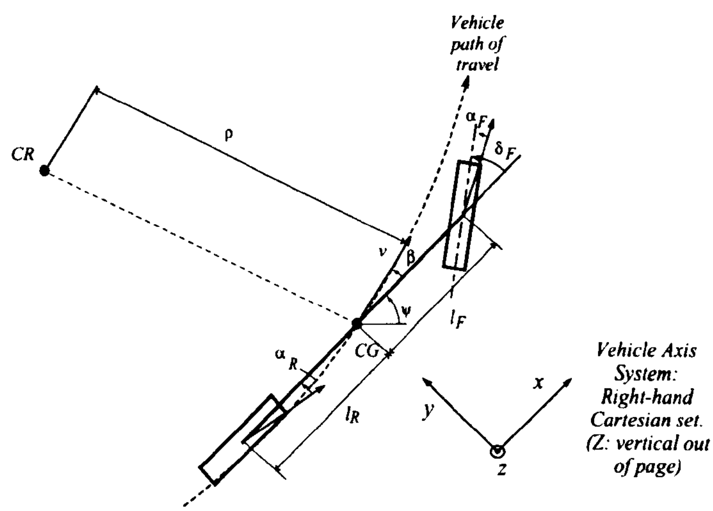

Figure 5.1: Kinematic quantities and geometry for the Single Track Model

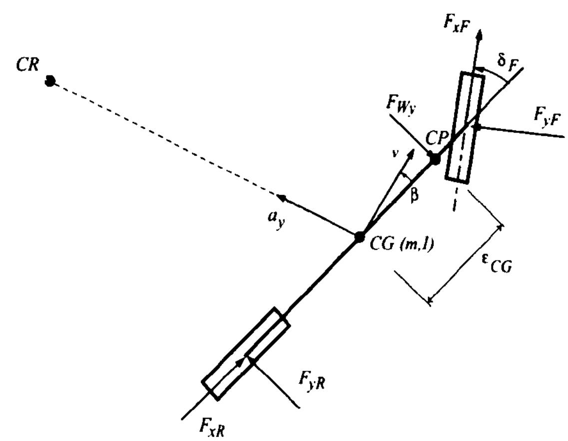

Figure 5.2: Forces for the Single Track Model

Equilibrium for moments around the Vertical Axis:

$$I_z \ddot{\psi} - (F_{yF} \cos \delta_F + F_{xF} \sin \delta_F) l_F + F_{yR} l_R + F_{Wy} \varepsilon_{CG} = 0 \tag{5.2}$$

The lateral acceleration, a_y in equation 5.1, can be expressed in terms of the vehicle's forward velocity, v_x, and the rate of change of the slip and yaw angles. Figure 5.3 shows the velocities at two points in time [Dixon 1996]. The vehicle has the angular velocity $\dot{\psi}$ and thus the vehicle's relative rotation is $\dot{\psi}\, dt$. The absolute lateral acceleration in the vehicle's y direction over the time interval dt is then given by:

$$a_y\, dt = dv_y\, cos(\dot{\psi}\, dt) + v_x sin(\dot{\psi}\, dt) \tag{5.3}$$

Taking into account small angles equation 5.3 becomes:

$$a_y\, dt = dv_y + v_x \dot{\psi}\, dt \tag{5.4}$$

$$a_y = \dot{v}_y + v_x\dot{\psi} \tag{5.5}$$

Differentiating the slip angle relationship, $\beta = v_y/v_x$, yields:

$$\dot{\beta} = \frac{1}{v_x}\frac{dv_y}{dt} - \frac{dv_x}{dt}\frac{1}{{v_x}^2} \tag{5.6}$$

When the forward velocity is constant $dv_x/dt = 0$, the lateral velocity can be written:

$$\dot{v}_y = \dot{\beta}v_x \tag{5.7}$$

Substituting equation 5.7 into 5.5 yields the expression for lateral acceleration:

$$a_y = v_x(\dot{\psi} + \dot{\beta}) \tag{5.8}$$

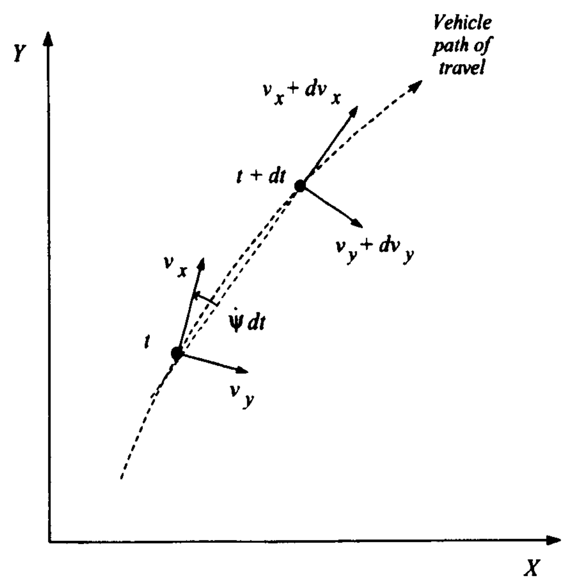

Figure 5.3: The velocity components at times t and dt on the vehicle path.

Taking into account no wind ($F_W = 0$) and small angles and substituting equation 5.8 into equation 5.1, the equations reduce to:

$$m\,v_x(\dot{\psi} + \dot{\beta}) = F_{yF} + F_{yR} \tag{5.9}$$

$$I_z\,\ddot{\psi} = F_{yF}l_F - F_{yR}l_R \tag{5.10}$$

While the wheel slip angles (also assuming small angles) are:

$$\alpha_F = -\beta + \delta_F - l_F\frac{\dot{\psi}}{v_x} \tag{5.11}$$

$$\alpha_R = -\beta + l_R\frac{\dot{\psi}}{v_x} \tag{5.12}$$

The side forces are defined as proportional to the wheel slip angles; thus:

$$F_{yF} = C_F \alpha_F, \quad F_{yR} = C_R \alpha_R \tag{5.13}$$

The differential equations for the model result by combining the equations 5.9 and 5.10 with the equations 5.13, 5.11 and 5.12:

$$mv_x(\dot{\psi} + \dot{\beta}) = c_F(-\beta + \delta_F - l_F \frac{\dot{\psi}}{v_x}) + c_R(-\beta + l_R \frac{\dot{\psi}}{v_x}) \tag{5.14}$$

$$I_z \ddot{\psi} = c_F l_F(-\beta + \delta_F - l_F \frac{\dot{\psi}}{v_x}) - c_R l_R(-\beta + l_R \frac{\dot{\psi}}{v_x}) \tag{5.15}$$

Thus, for a given forward velocity, v_x, and front wheel angle, δ_F, the vehicle's slip angle, β, and yaw rate, $\dot{\psi}$, can be calculated.

5.2.2 Steering Model

The steering model is made up of two separate bodies as can be seen in figure 5.4. The first body incorporates the road wheel, track rod, steering rack and pinion and the portion of the steering column below the Hardy disc. (This is not a detailed model of the track rod and its connections. Its purpose is to deliver a representative force to the steering rack.) The second body is made up of the steering column above the Hardy disc and the steering wheel. These two bodies are connected by a single spring representing the combined stiffness (equation 5.19) of the torsion bar and Hardy disc and a damper.

Equations of Motion

Based on figure 5.4, the following differential equations of motion can be derived for the Hand Wheel/Steering Column body, equation 5.16, and the Road Wheel/Steering Rack body, equation 5.17. Moments are taken around the kingpin axis [1] (see section 1.3.2) for this body.

$$I_H \ddot{\delta}_H = -c_S(\delta_H - i\delta_F) - d_S(\dot{\delta}_R - i\dot{\delta}_F) - M_{Fr} \tag{5.16}$$

$$(I_F + m_F {n_c}^2)\ddot{\delta}_F = iM_H - n_c F_F - {n_s}^2 d_Z \dot{\delta}_F - n_s F_{Fr} + n_s F_{Servo} - M_Z \tag{5.17}$$

where:

$$M_H = c_S(\delta_H - i\delta_F) + d_S(\dot{\delta}_R - i\dot{\delta}_F) \ , \tag{5.18}$$

$$c_S = \frac{C_H C_T}{C_H + C_T} \quad \text{and} \quad i = \frac{n_s}{n_r} \tag{5.19}$$

[1] The kingpin axis is not the centre of mass of the wheel or a stationary point, as the vehicle is being driven. Taking moments about a non-fixed point, or a point whose velocity is not parallel to that of the centre of mass of the body, leads to an approximation of the dynamic equations of motion. However, the inertial effects contributing to an error in taking moments about the kingpin axis are negligible at this low frequency (see appendix section A.2, figure A.2). This approximation was also included in [Segel 1983] when moments were similarly taken around the kingpin axis.

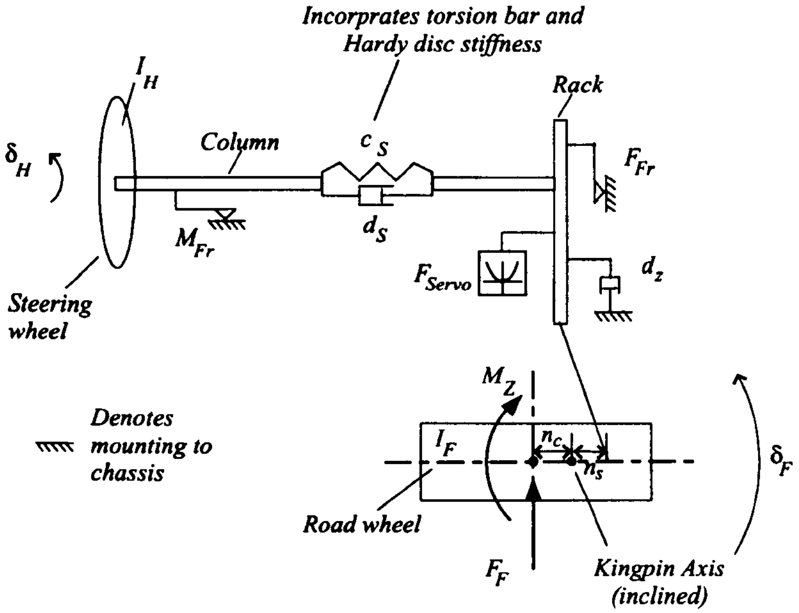

Figure 5.4: The steering model

Modelling the Power Assistance

The power assistance force, F_{servo} is derived according to equation 5.20. H_{cc} is the steering valve characteristic curve obtained from measurement. The curve relates the torsion bar deflection, δ_T, to the assistance pressure delivered at the hydraulic piston. A similar method is used by Kim [1997] when modelling on-centre handling.

$$F_{Servo} = \delta_T.H_{cc}.A_P \tag{5.20}$$

$$\delta_T = \frac{\delta_H}{1 + \frac{C_T}{C_H}} \tag{5.21}$$

Friction Modelling

The friction is modelled with Dahl's Friction Model, [Bliman 1992]. The friction force is dependent on the velocity, $\dot{x}$, between the two bodies involved. The model is based on the following equation 5.22:

$$\dot{F}_{Fr} = \sigma\, \dot{x}| - \frac{F_{Fr}}{F_c} Sign[\dot{x}]|^{i_D} .Sign(1 - \frac{F_{Fr}}{F_c} Sign[\dot{x}]) \tag{5.22}$$

The parameters σ and i_D control the shape of the hysteresis loop while F_c denotes the magnitude of Coulomb friction. The mathematical consistency of this model as a hysteresis operator is proven in a study by Bliman [1992], while Galvez [2000] uses and validates the model for the simulation of straight running quality.

Modelling Play

The model also features the variable δ_P to introduce free play into the steering column (figure 5.5). This is utilised according to equation 5.23. Where δ_{Hi} denotes the input rotation, δ_{Ho} the output rotation and δ_P is defined as the total input range for which the output is zero.

$$\text{If } \delta_{Hi} < 0, \quad \delta_{Ho} = min(0, \delta_{Hi} + \tfrac{\delta_P}{2}), \quad \text{else } \delta_{Ho} = max(0, \delta_{Hi} - \frac{\delta_P}{2}) \qquad (5.23)$$

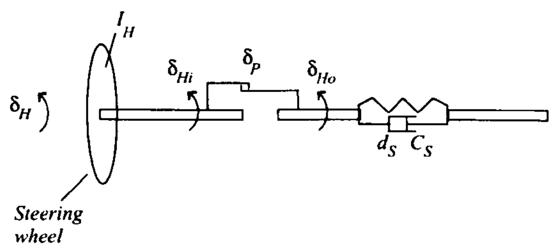

Figure 5.5: Modelling clearance in the steering column.

5.2.3 Tyre Forces

The equations in section 5.2.1 are based on a linear tyre model where the side force is proportional to the slip angle (equation 5.13). In reality, the relationship is non-linear as the tyre forces saturate at large slip angles as explained in section 1.3.3.

To incorporate the non-linear tyre properties in the simulation, another more complicated vehicle model was employed. This model provided the required non-linear relationships between the lateral tyre force (F_y) and aligning moment(M_Z) to the slip angles (α) for the front axle.

The Two Track Vehicle Model

A twin track vehicle model developed in-house at BMW was used to provide a more accurate representation of the tyre forces and moments [Beiker 2000]. This model is based on characteristic curves describing the input/output properties of the vehicle sub-systems. These characteristics are derived from vehicle dynamic measurement, component testing, vehicle testing on rigs, and multi-body simulation results.

The vehicle has the following degrees of freedom: Longitudinal, lateral and vertical translations; pitch, roll and yaw. Characteristic curves describe the movement of the wheels independently. For the vertical position of each wheel there is a corresponding camber angle, caster angle and half track width, reflecting the suspension kinematics and the elastokinematic influence. The steering in this case is rigid and is not hydraulically assisted. Pacejka's [1996] Magic Formula Model 96 is employed as a tyre model. For a quasi-stationary circle manœuvre at a radius of 40 m, the two track vehicle model produced results representing the tyre side force and aligning moment at each of the front wheels.

The bicycle model represents the axles by a single wheel. The results from the two track model's inner and outer tracks were combined to produce a single relationship by adding the forces and moments, right and left, and taking an average of the slip angle, right and left. Such an approximation is unavoidable when modelling a two track vehicle with a bicycle model. The curves in figures 5.6 and 5.7 represent the total side force and total aligning moment relationships to slip angle derived from the twin track model.

The integration of the output of the larger model into the single track vehicle model, incorporating the steering system, was achieved by using the characteristic curves to produce a tyre lateral force and aligning moment for a given slip angle. The aligning moment was then input into the steering model as the term M_Z in equation 5.17. The lateral force was input into the vehicle model as the term F_{yF} in equation 5.10, which replaced the relationship for F_{yF} in equation 5.13. It also features as F_F in the steering model in equation 5.17.

5.2.4 Integration of the Models

In order to simulate the entire vehicle, the steering and tyre models were integrated with the vehicle model. The model is controlled via a steering angle input [2]. This defined input, δ_H, is administered to the steering model, which produces a displacement to the road wheel/steering rack body, δ_F. This road wheel angle is input into the bicycle model and thus steers the vehicle. The bicycle model generates slip angles which, through the tyre characteristic curves generated by the larger BMW model, generate side force, F_{yF}, and aligning moment, M_Z, at the front axle. These are, in turn, input back into the steering model.

[2]The inertial effects of the steering wheel are negligible at low frequencies when compared to the torques acting on the steering column (see appendix A.2, figure A.3)

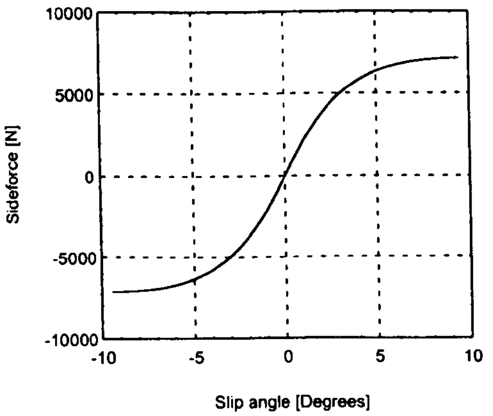

Figure 5.6: Curve representing the total lateral tyre force generated by both front wheels derived from the two track model for input into the bicycle model.

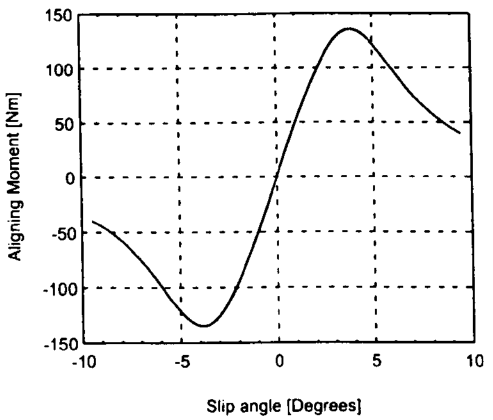

Figure 5.7: Curve representing the total aligning moment generated by both front wheels derived from the two track model for input into the steering model.

5.2.5 Simulating the Manœuvres

The three manœuvres concentrated on in section 4.4, the weave, transition, and stationary circular tests were simulated using the integrated vehicle-steering-tyre model. These are referred to as 'Weave Test Simulation', 'Transition Test Simulation' and 'Stationary Circle Test Simulation' in this and following chapters.

The weave test was simulated using a constant 100 km/h longitudinal velocity input. A sinusoidal steering wheel angle at 0.2 Hz was input at an amplitude consistent with that measured from the vehicle objective testing. The transition test manœuvre also involved a constant velocity input of 100 km/h. A ramp input was employed for the steering wheel angle at a rate of 5°/s. A similar ramp input was used for the stationary circle test simulation to input the vehicle's velocity at a rate of 0.5 $m/s/s$, so that the dynamic effects had no influence on the result. The steering wheel angle was increased[3] so that the vehicle remained on the 40 m radius path.

5.3 Simulation Results

The vehicle model, including the steering model, was used to simulate the three major tests described in chapter 4. Validation of the model is achieved by comparison with the measured data gathered during testing, a principle recommended by Heydinger, Garrott, Chrstos & Guenther [1990]. The same quality experiment outlined in chapter 2 and executed by vehicle testing was performed with the simulation model. The variable parameters, and only these parameters, were modified according to their measured values in section 4.3, component testing. The main purpose of the simulation is to indicate the trends observed during parameter variation. This is presented in the discussion in chapter 6. The simulation results are presented alongside the test results in this chapter for validation.

5.3.1 Weave Test Simulation

Of the three tests, the weave test produces the closest prediction of the vehicle's behaviour. This is understandable since the transition and stationary circle tests deal with the regions most affected by the non-linearities. The simulation results are presented as cross plots as the test results were in chapter 4. Both the simulation results and the corresponding measurements are presented in the same plots for comparison. The standard configuration is depicted in figure 5.8 and the most extreme parameter variations are plotted in the following figures.

Effect of Extra Compliance

As seen in the measurements (section 4.4.1), the elasticity did not have a dramatic effect on the hysteresis. The extra compliance altered the gradient of the whole hysteresis loop. This was achieved in the simulation by substituting the Hardy disc stiffness with that of the more compliant disc. The same effect on the overall gradient is evident in the simulation (figure 5.9). The stiffness representing the disc was then increased to that of the aluminium steering column to represent the aluminium element, which replaced the Hardy disc. The model produced a similar small reaction to this variation as in the test (figure 5.10) .

Effect of Extra Column Friction

The model shows how, as with the vehicle testing measurements, the system hysteresis is greatly increased by the column friction (figure 5.11). This is implemented using

[3]This was achieved using a formula derived from the linear bicycle model according to Mitschke [1990] (see appendix A.3).

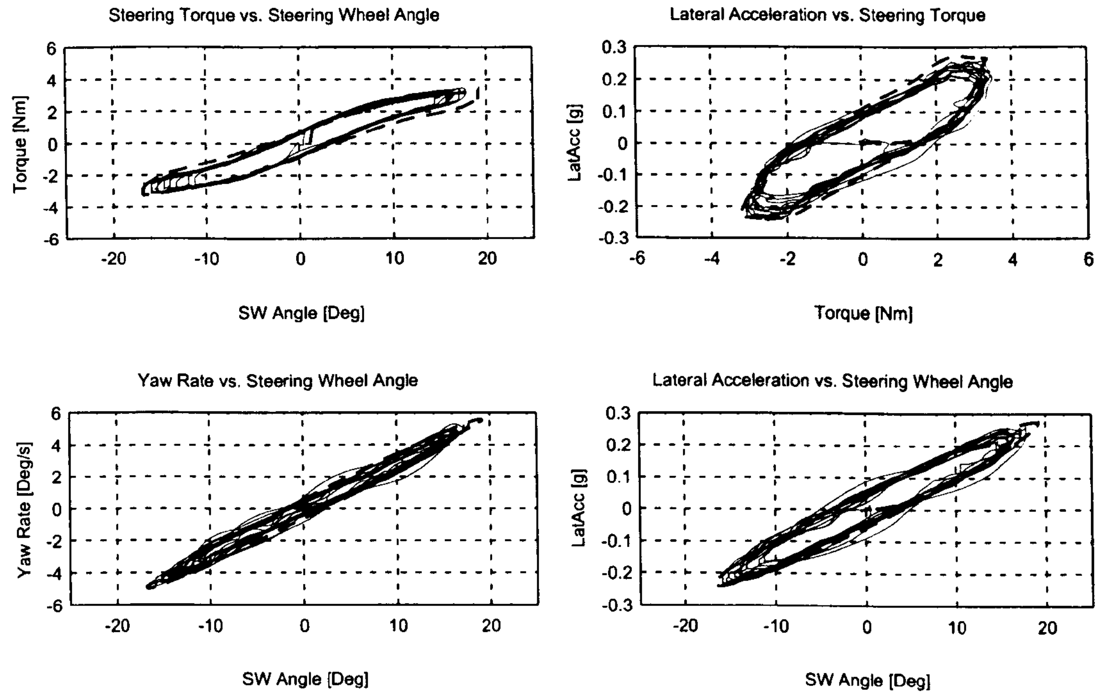

Figure 5.8: Weave test simulation cross plots - **Standard Vehicle Configuration**. Measurement - continuous line. Simulation - dashed line.

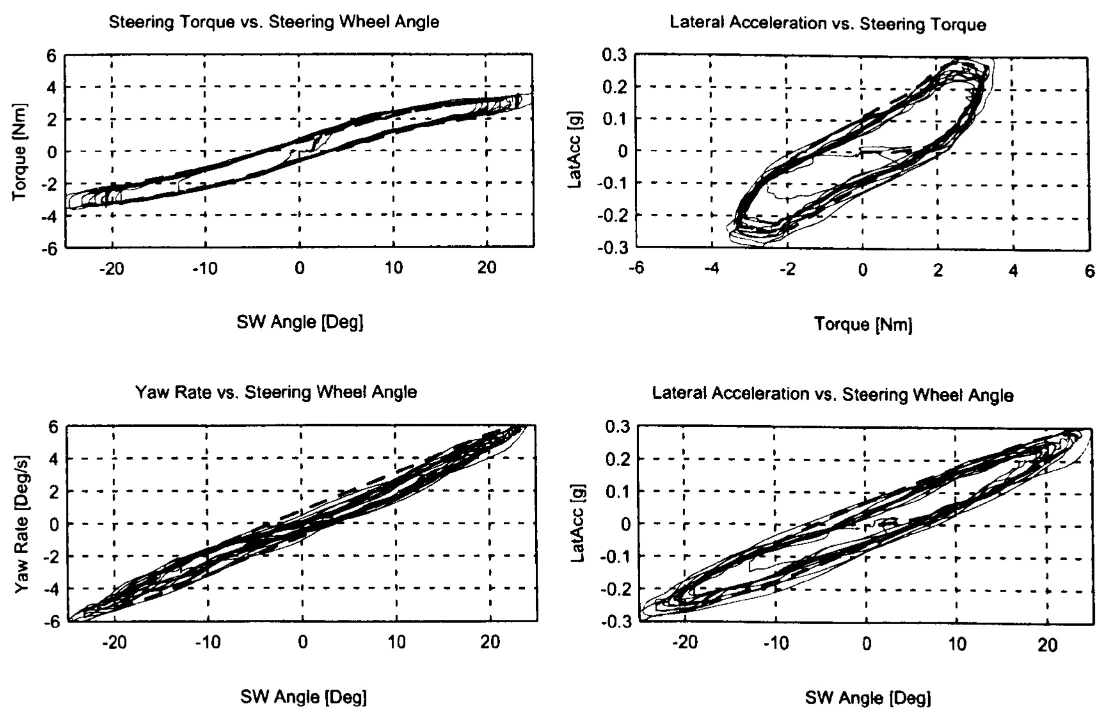

Figure 5.9: Weave test simulation cross plots - **Maximum Compliance Configuration**. Measurement - continuous line. Simulation - dashed line.

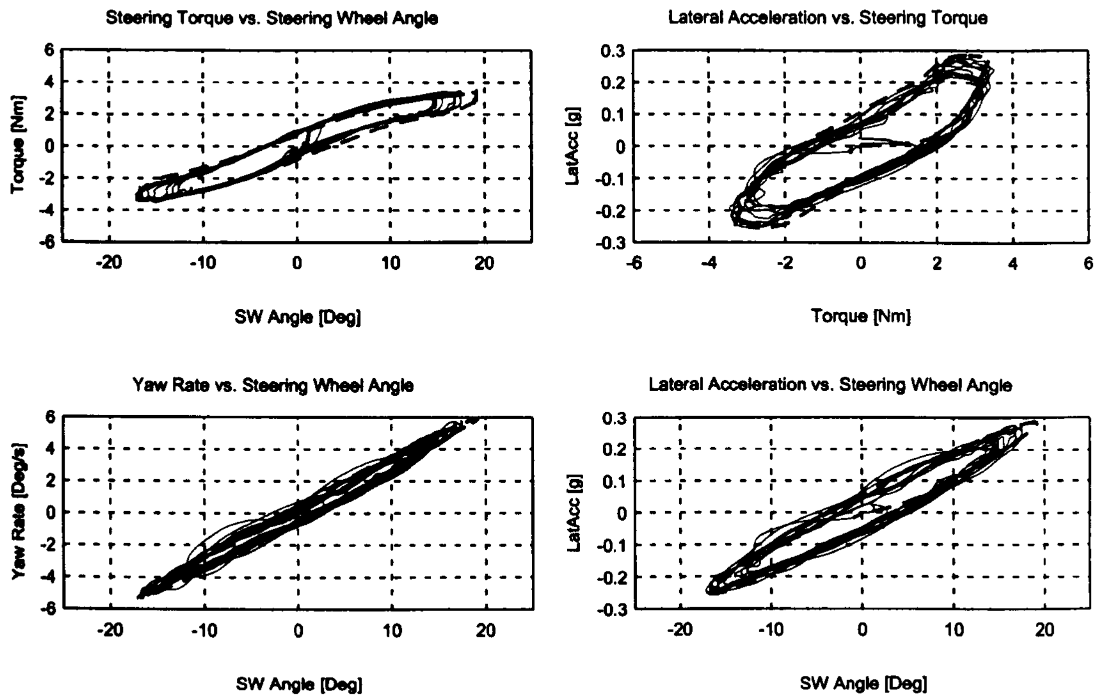

Figure 5.10: Weave test simulation cross plots - **Maximum Stiffness Configuration**. Measurement - continuous line. Simulation - dashed line.

the Dahl model (section 5.2) as a hysteresis operator and results in a similar expansion of the cross plot loops for the steering torque curves, while the plots depicting the vehicle reaction to steering angle remain largely unaffected.

Effect of Extra Rack Friction

The simulation was useful in examining the secondary effect of the rack friction, which altered the vehicle's response to the steering angle input (figure 5.12). This, not so obvious, result was also evident in the model and could be further investigated with levels of friction not so easily achievable in the vehicle. Similar to the column friction result, the rack friction variation produces a widening of the hysteresis loops describing the torque relationship.

Effect of Extra Power Assistance

The measurement of the hydraulic valve characteristics provided separate characteristic curves for use in the modelling of the assistance via equation 5.20 in section 5.2.2. These, when input into the simulation, almost exactly reproduced the difference in assistance levels achieved in the vehicle testing (figures 5.13 and 5.14).

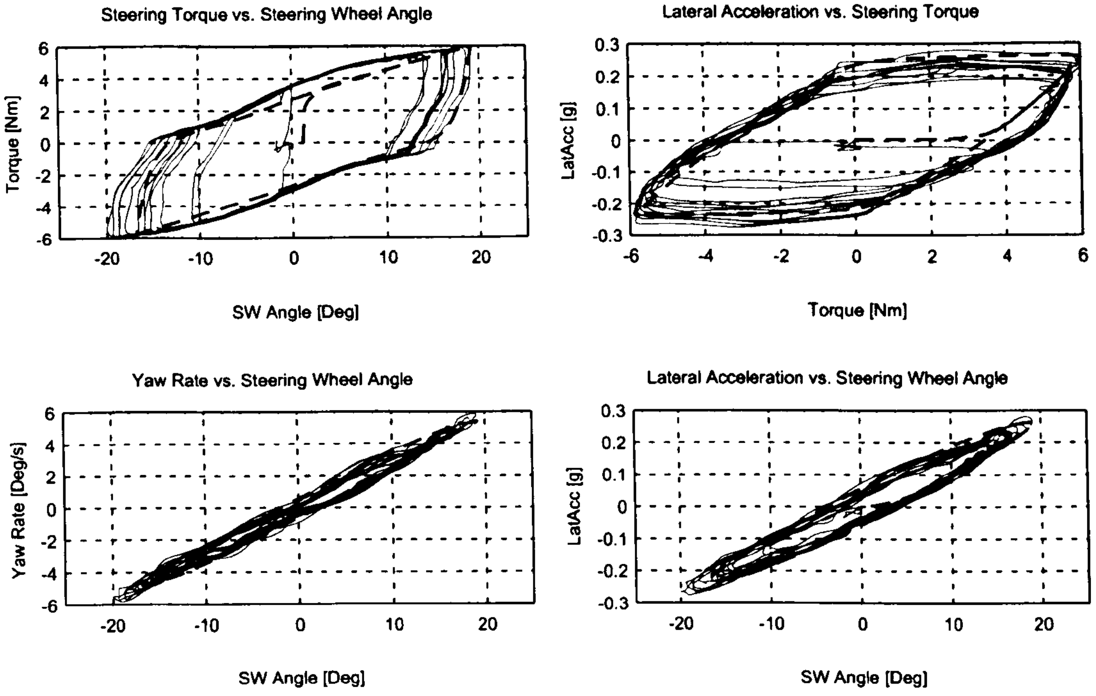

Figure 5.11: Weave test simulation cross plots - **Maximum Column Friction.** Measurement - continuous line. Simulation - dashed line.

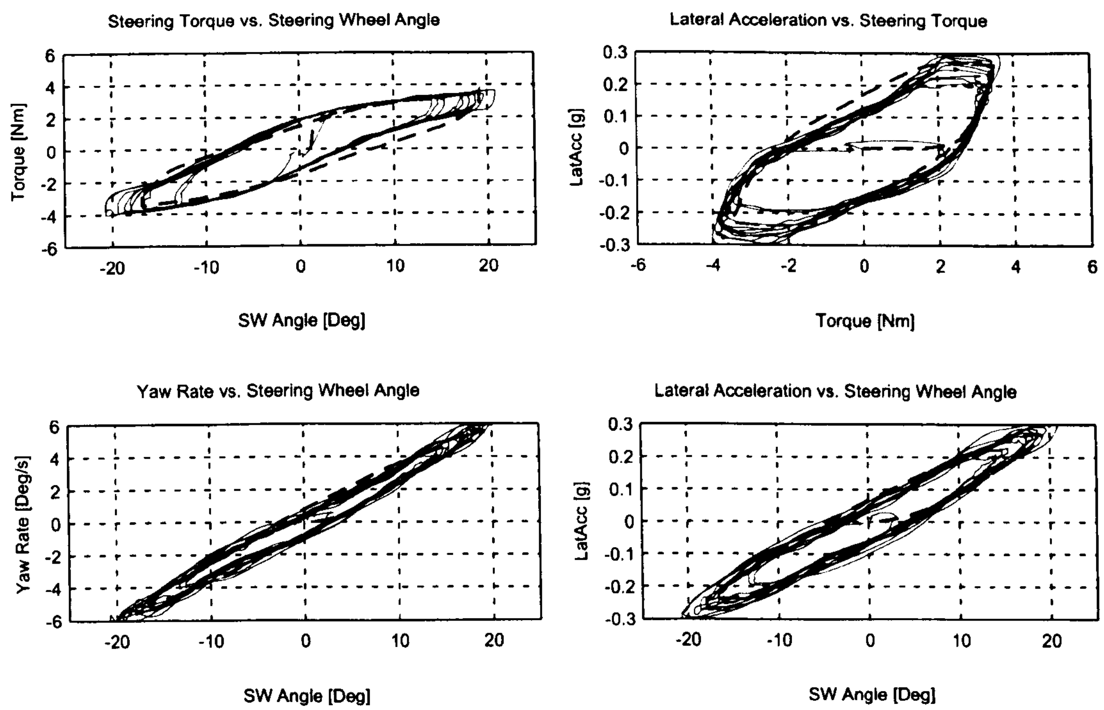

Figure 5.12: Weave test simulation cross plots - **Maximum Rack Friction.** Measurement - continuous line. Simulation - dashed line.

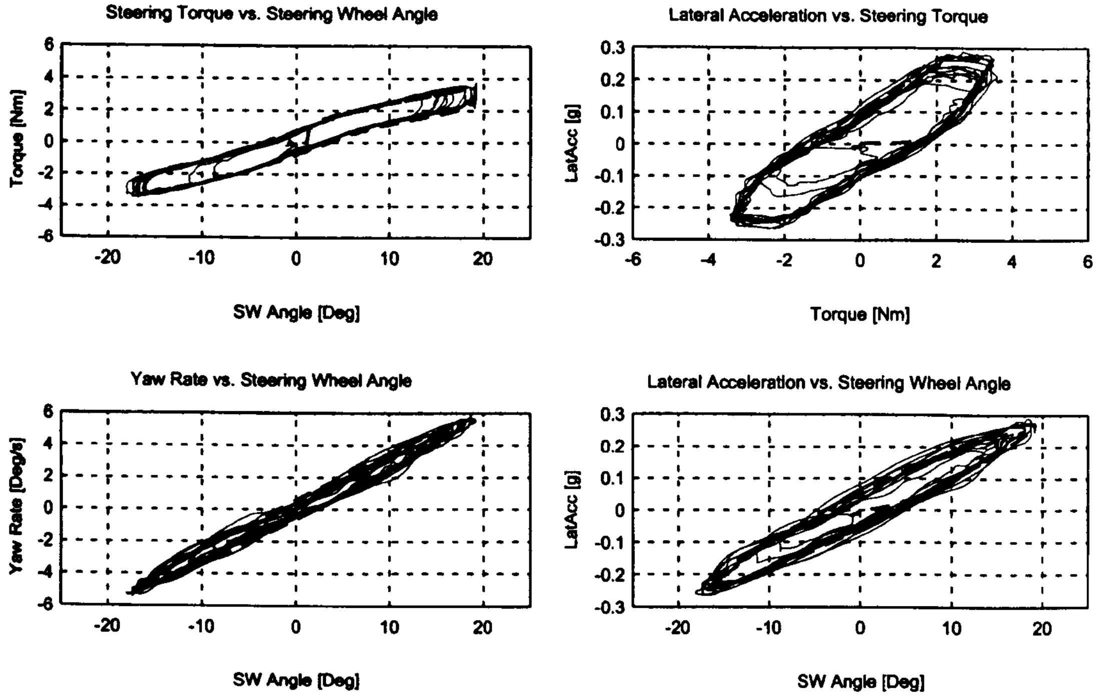

Figure 5.13: Weave test simulation cross plots - Servotronic® - **Standard configuration**. Measurement - continuous line. Simulation - dashed line.

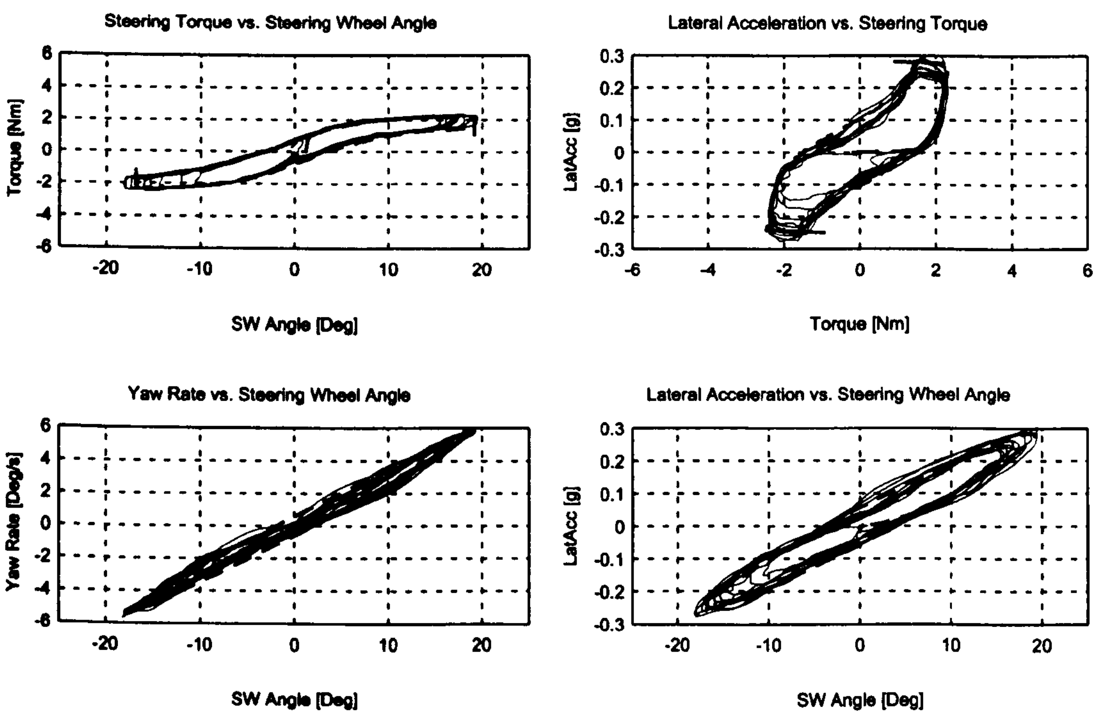

Figure 5.14: Weave test simulation cross plots - Servotronic® - **Maximum Assistance**. Measurement - continuous line. Simulation - dashed line.

Effect of Extra Free Play

The free play introduced a dead zone in the on-centre region, which flattened the centre and disjointed the hysteresis loops of the test results. The presence of play in the model has the same outcome in the modelling of the weave test as is clearly depicted in figure 5.15.

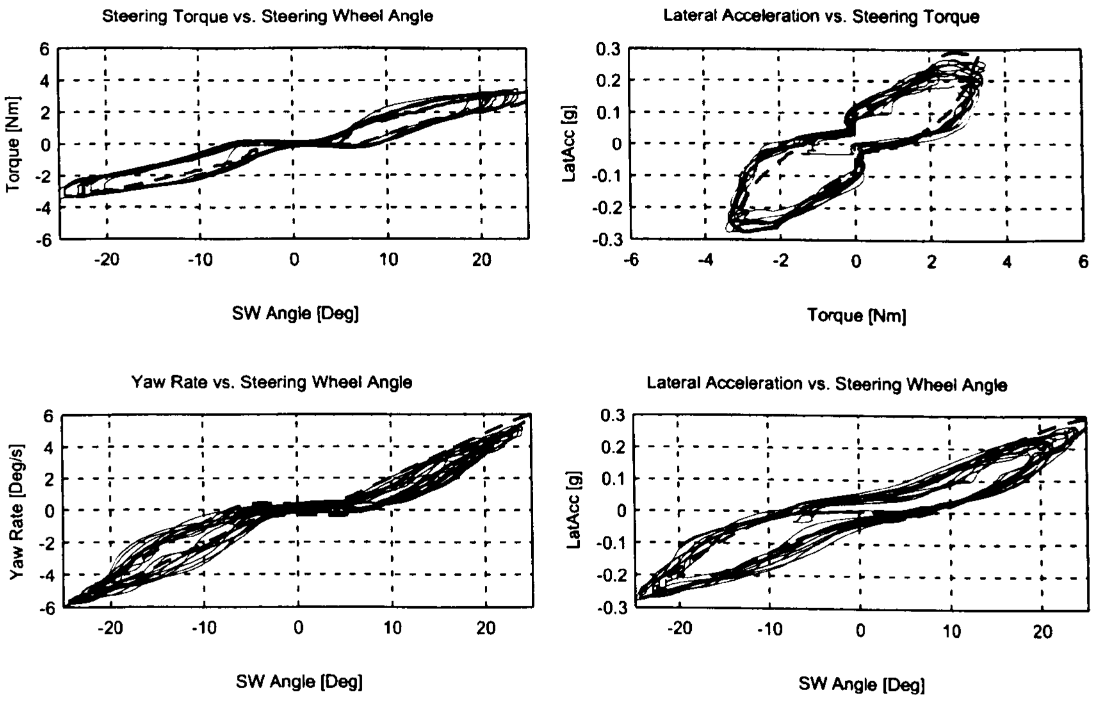

Figure 5.15: Weave test simulation cross plots - **Maximum Free Play**. Measurement - continuous line. Simulation - dashed line.

5.3.2 Transition Test Simulation

The transition test is performed in a region of vehicle handling where the non-linearities have a considerable effect. It is therefore the non-linearities in the model such as the friction, the play and the power assistance, which contribute to its accurate representation. Therefore, the linear effects that are easier to model are less dominant and the result is less accuracy than for the weave test where the linear behaviour is stronger. Figure 5.16 shows the standard configuration of the vehicle as measured alongside the simulation. Although the correlation of the results is not perfect, the differences caused by each variation are reflected in the model as in the vehicle tests.

Effect of Extra Compliance

It is the compliance acting in tandem with the friction, which increases the non-linearity of the vehicle response to the steering angle. The gradient is also altered (figure 5.17). The torque/vehicle response relationship is only marginally changed in the measurements. In the simulation, this is even less evident, suggesting that any change noticed in the relationship is caused by measurement noise or external factors. Increasing the stiffness, as in figure 5.18, has a minimal effect as in the testing.

Effect of Extra Column Friction

As with the weave test simulation, the transition test shows, as a consequence of added column friction, a decidedly different torque to vehicle reaction relationship. The dead zone is increased where the torque rises without any reaction (figure 5.19). Similar to the weave test simulation, the transition test confirms no alteration in the vehicle response to steer angle with extra column friction.

Effect of Extra Rack Friction

The more complicated effects of increasing the rack friction make for more difficult modelling. Figure 5.20 demonstrates how the simulation accurately predicts the alteration in relationships involving torque and the dead zones caused by the friction. The simulated vehicle lateral response to steering angle differs slightly in gradient to the measured response. However, the small difference in initial gradient, as compared with the standard configuration, remains similar to the difference shown in the measurements.

Effect of Extra Power Assistance

The result of more power assistance in the system is demonstrated in figure 5.21 in the three plots showing the steering torque. The reduction in torque is shown in both the test and model results, while the vehicle lateral reaction to steering angle is not much altered.

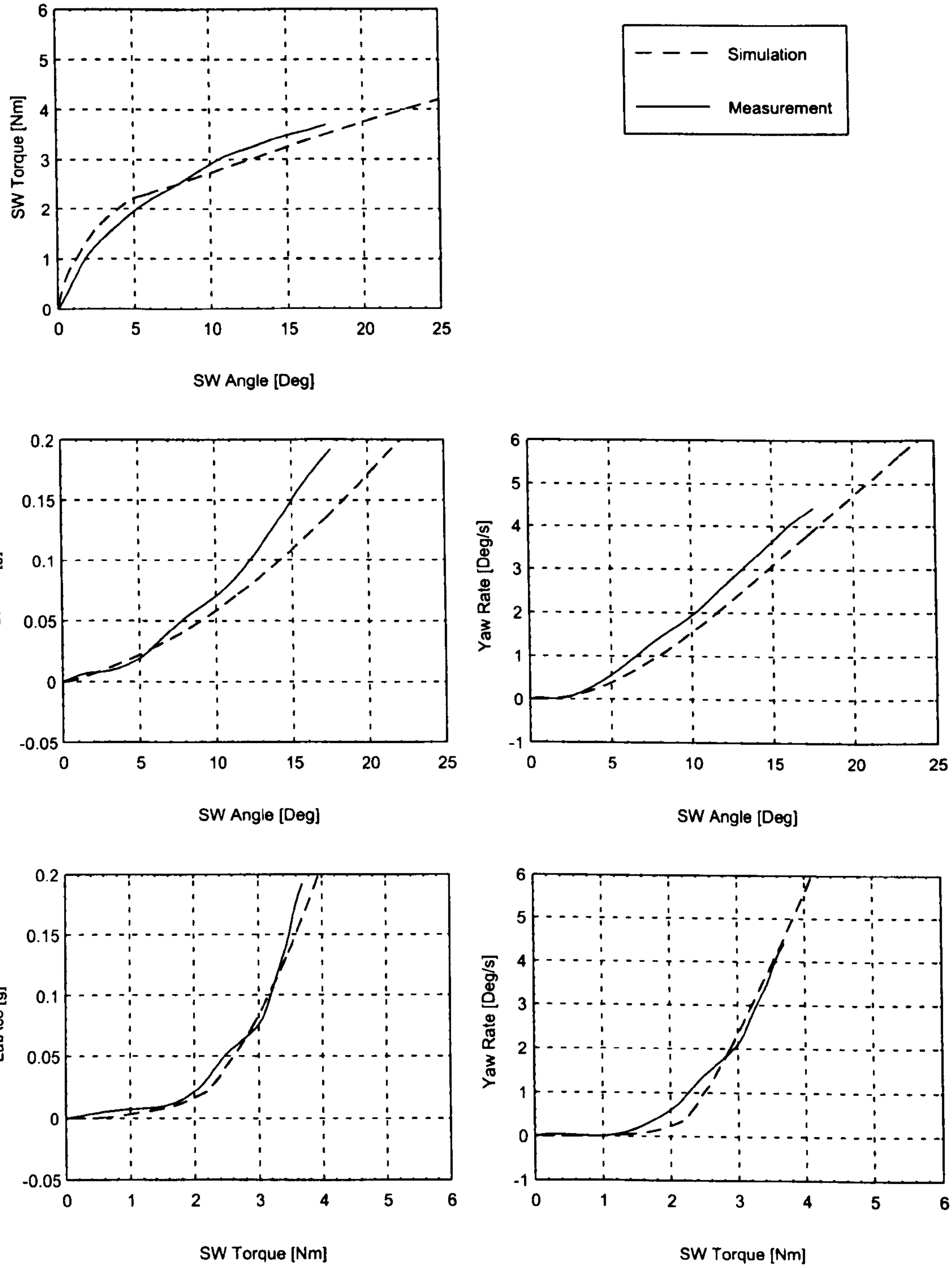

Figure 5.16: Transition test simulation - **Standard Vehicle Configuration**. Measurement - continuous line. Simulation - dashed line.

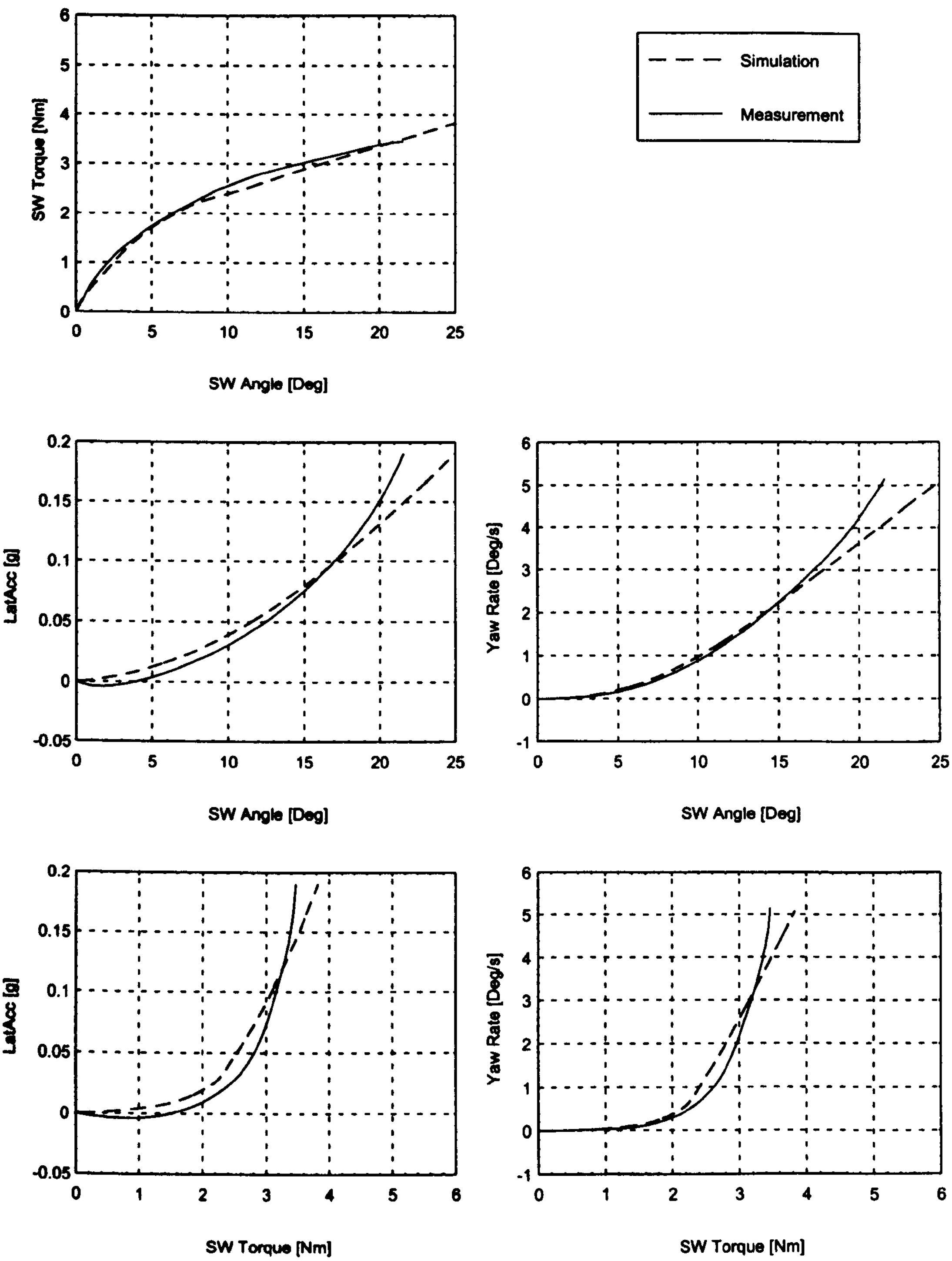

Figure 5.17: Transition test simulation - **Maximum Compliance Configuration.** Measurement - continuous line. Simulation - dashed line.

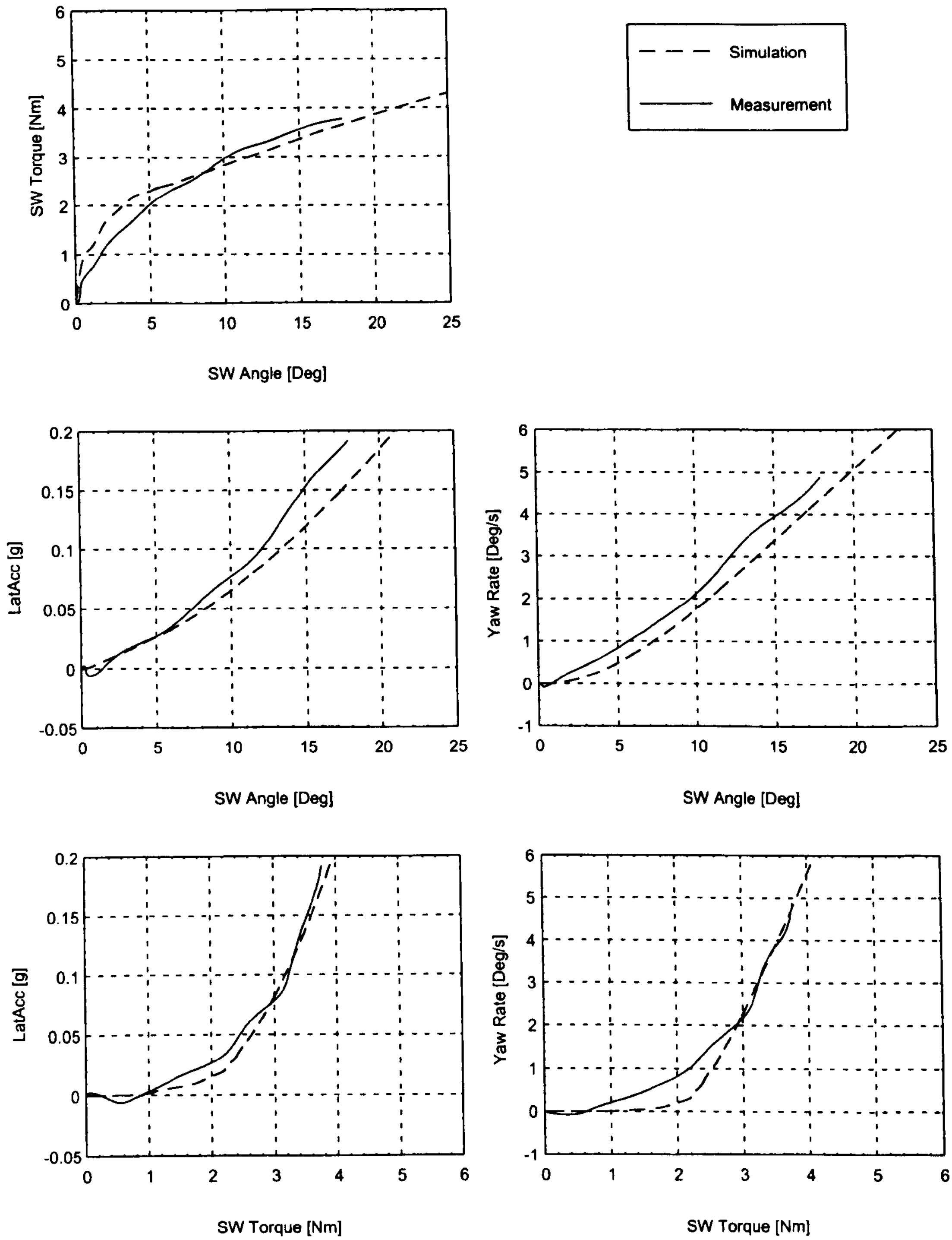

Figure 5.18: Transition test simulation - **Maximum Stiffness Configuration**. Measurement - continuous line. Simulation - dashed line.

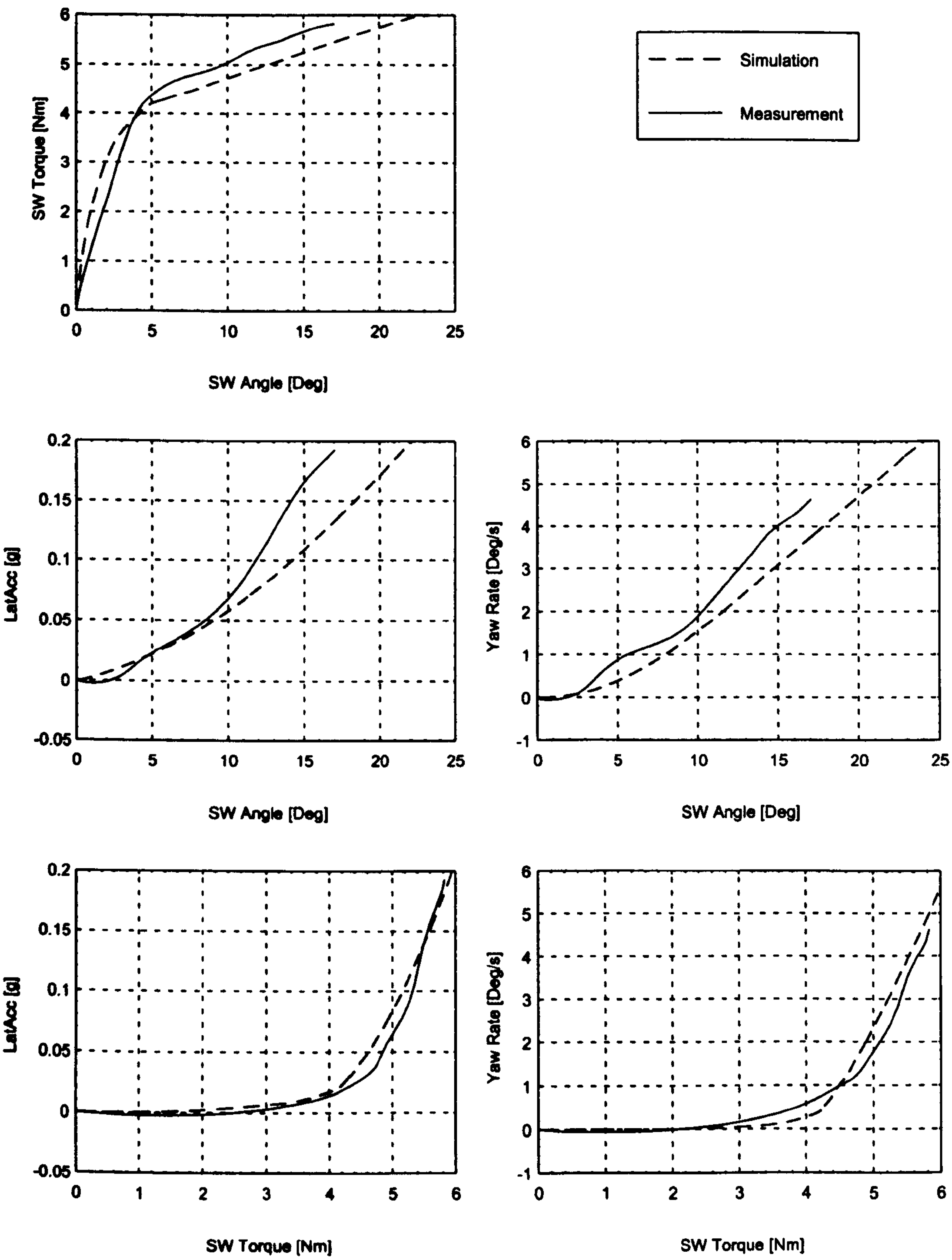

Figure 5.19: Transition test simulation - **Maximum Column Friction**. Measurement - continuous line. Simulation - dashed line.

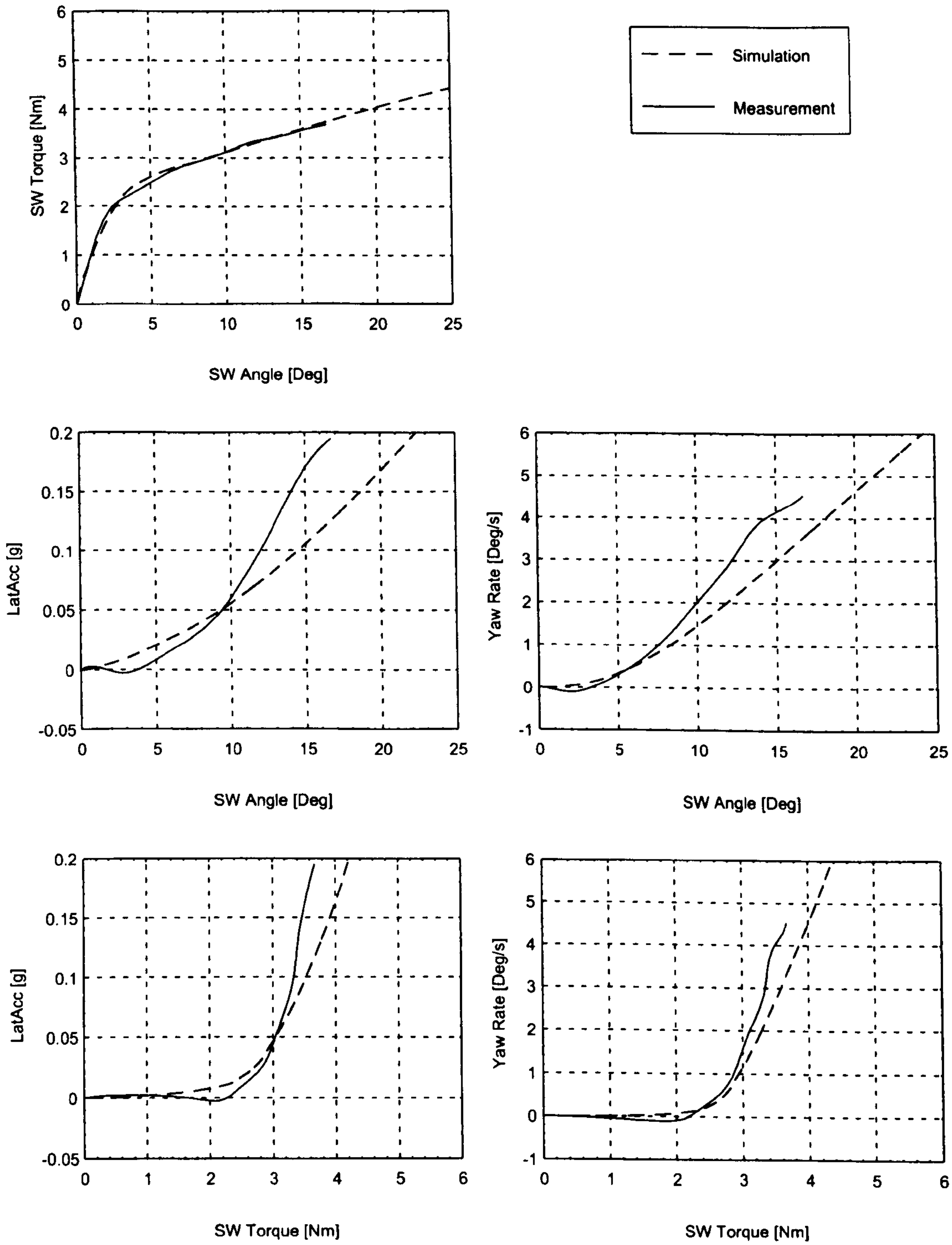

Figure 5.20: Transition test simulation - **Maximum Rack Friction**. Measurement - continuous line. Simulation - dashed line.

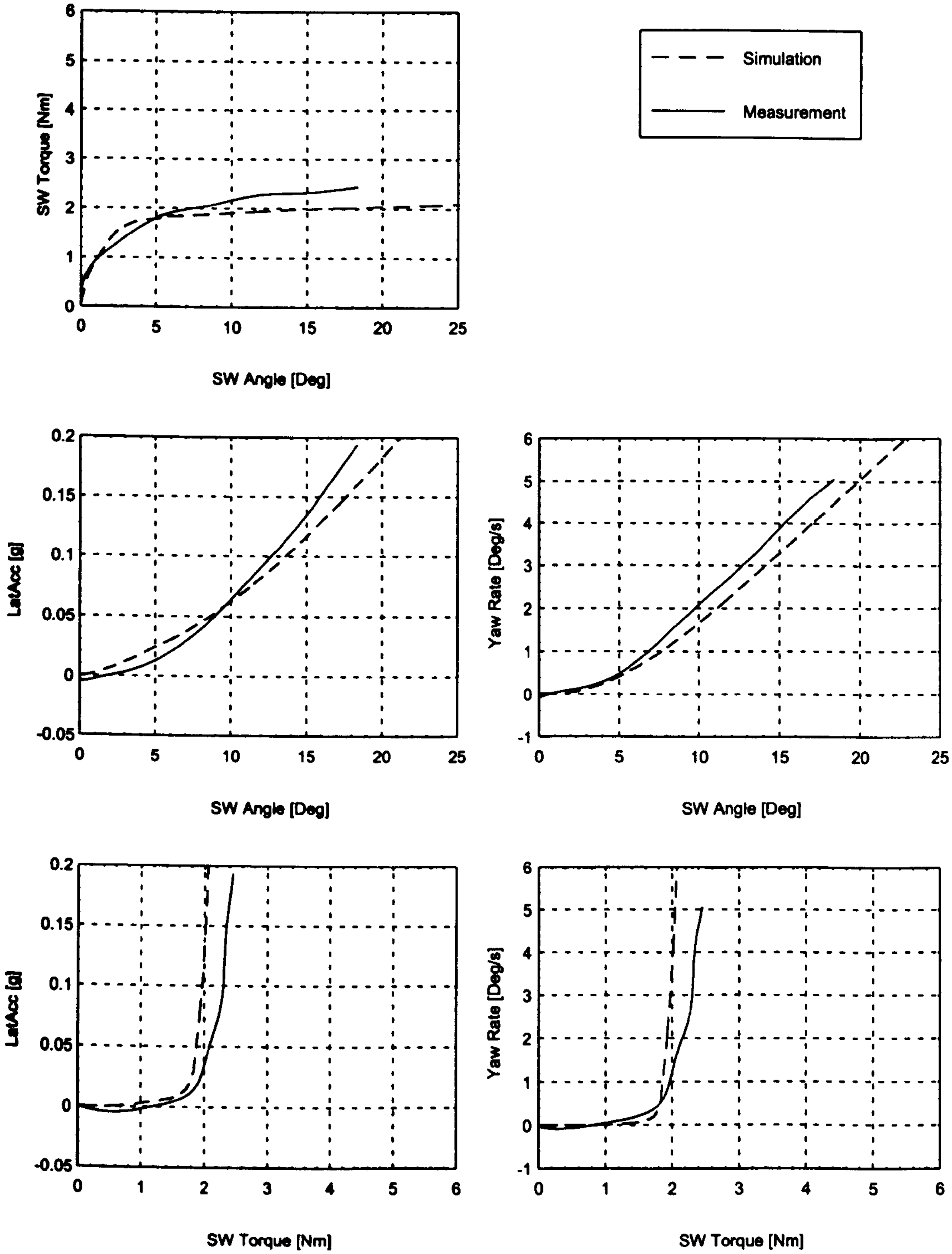

Figure 5.21: Transition test simulation - Servotronic® - **Maximum Assistance**. Measurement - continuous line. Simulation - dashed line.

Effect of Extra Free Play

The dead zone evident in the measurements when play is introduced, is mirrored almost exactly in the simulation results in figure 5.22. The influence of the different filter used for this measurement can be seen again here in the roughness of the curves.

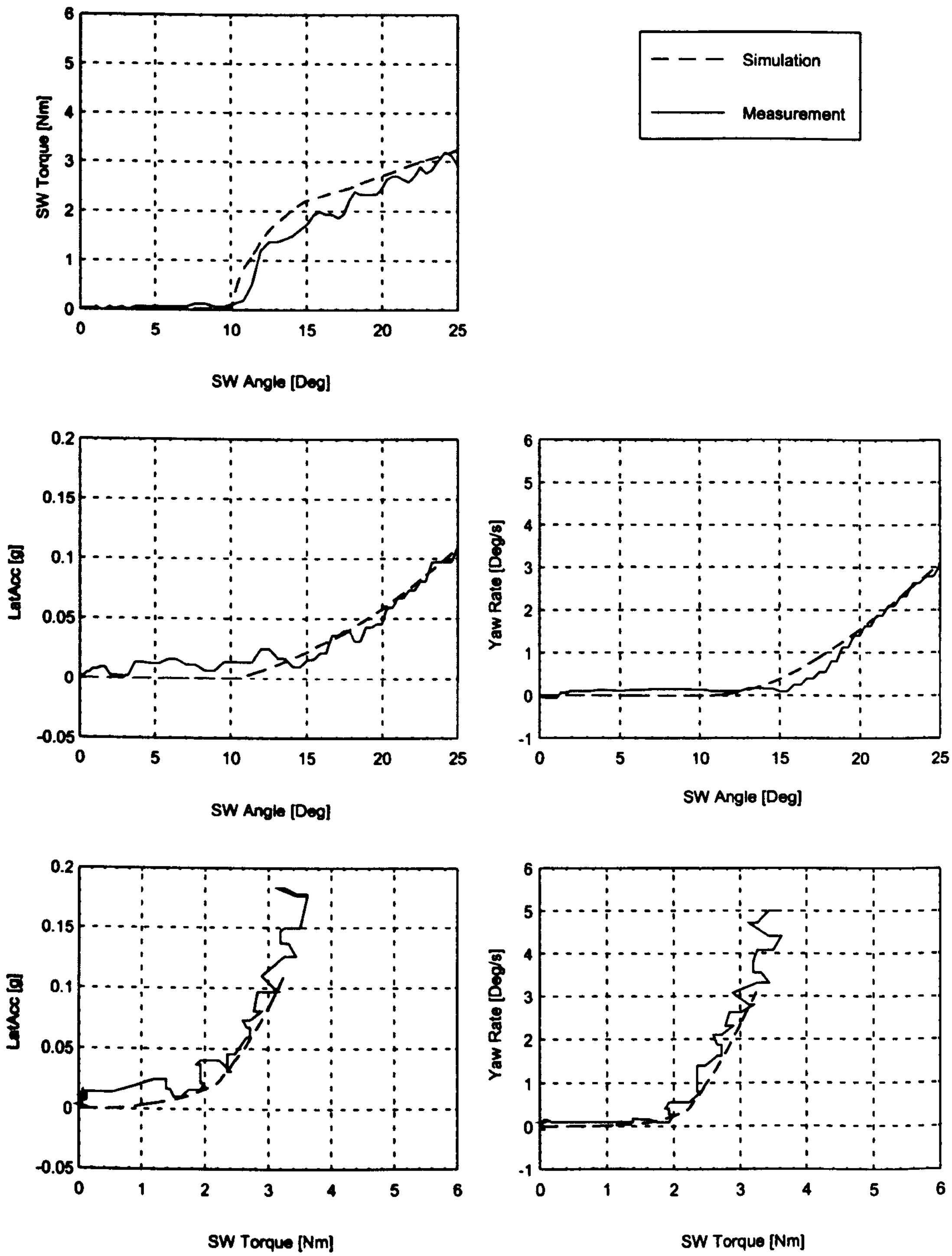

Figure 5.22: Transition test simulation - **Maximum Free Play**. Measurement - continuous line. Simulation - dashed line.

5.3.3 Stationary Circle Test Simulation

The circular test was simulated quasi-statically. The steering wheel angle was increased at such a low rate, that no dynamic effects occurred. Therefore, as distinct from simulating particular points and interpolating between them, the points in between were themselves simulated. Thus, there was a large number of points for comparison to the data points generated by testing.

Effect of Extra Compliance

There was little difference in the test results between the different levels of compliance examined. The differences in the simulation (figures 5.23, 5.24 and 5.25) are even less evident, further reinforcing that the differences seen in the measurements are due only to measurement noise, reflecting the lack of repeatability achieved with the test.

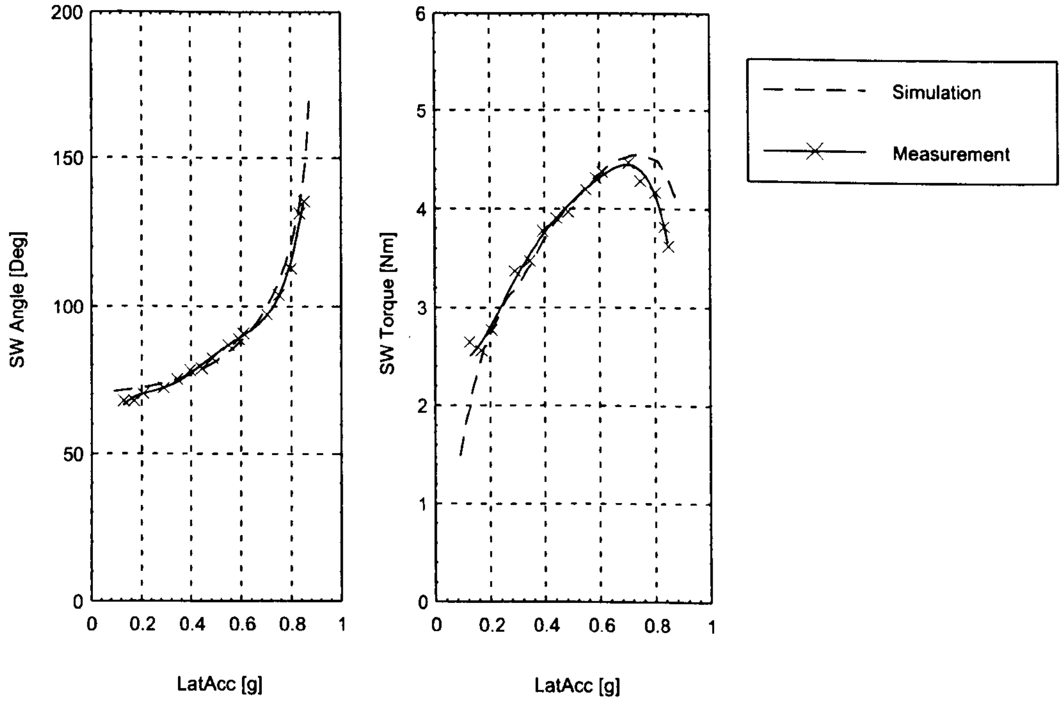

Figure 5.23: **Standard Configuration**. Stationary Circle Test Simulation - Radius = 40 m, Left.

Effect of Extra Column Friction

The circular test demonstrated that high column friction destroyed the correlation between the steering torque and the lateral acceleration. This was due to the friction bandwidth increasing so that a significant change in torque from the controller or the road wheels resulted in no movement of the steering column. The simulation of extra column friction (figure 5.26) demonstrates only an increase in torque but retains

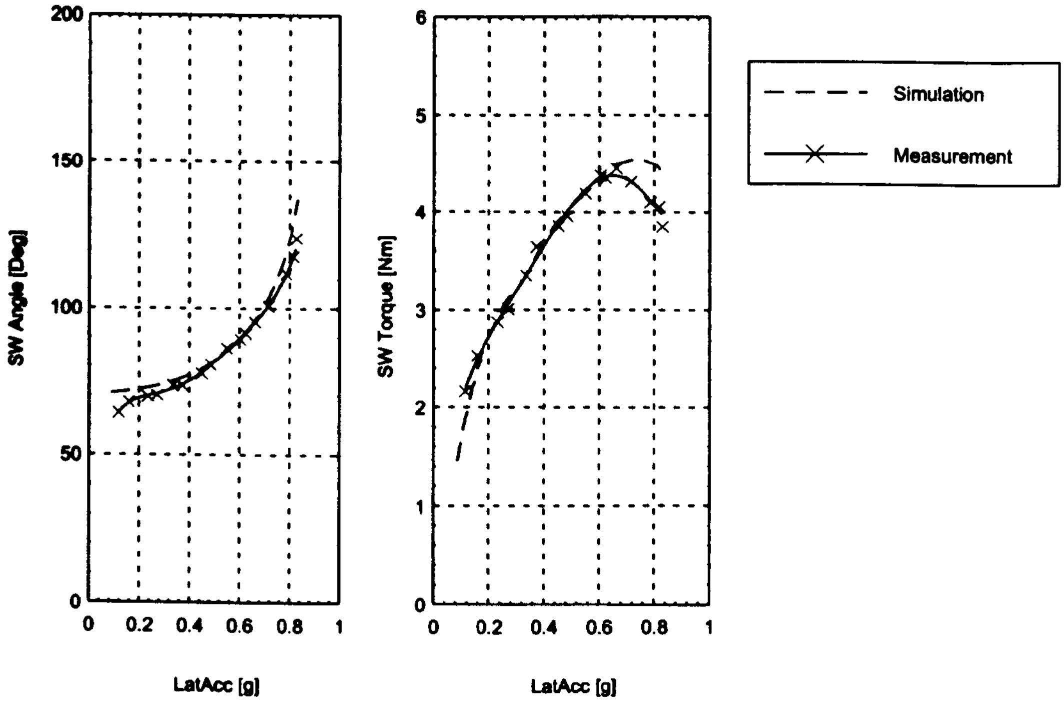

Figure 5.24: **Maximum Compliance**. Stationary Circle Test Simulation - Radius = 40 m, Left.

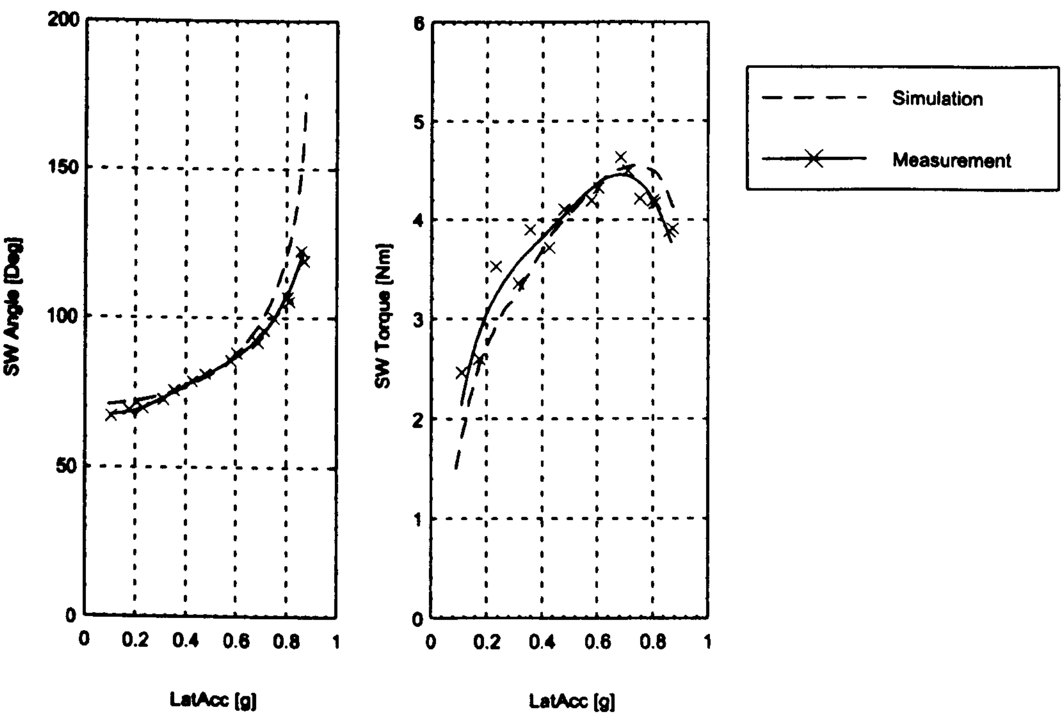

Figure 5.25: **Maximum Stiffness**. Stationary Circle Test Simulation - Radius = 40 m, Left.

correlation and even the torque drop-off. To demonstrate the effect of a change in input having an uncorrelated or double valued output, a different input was needed. A sinusoidal 'wobble', four degrees in amplitude, was input to the steering wheel during the manœuvre. The resulting plot (figure 5.27) demonstrates that only a small perturbation in the steering angle, which causes hardly any perturbation in the vehicle's lateral acceleration, yields a large output of steering torque, which is not correlated to the vehicle's lateral acceleration. This reflects the loss of correlation evident in the circular test measurement.

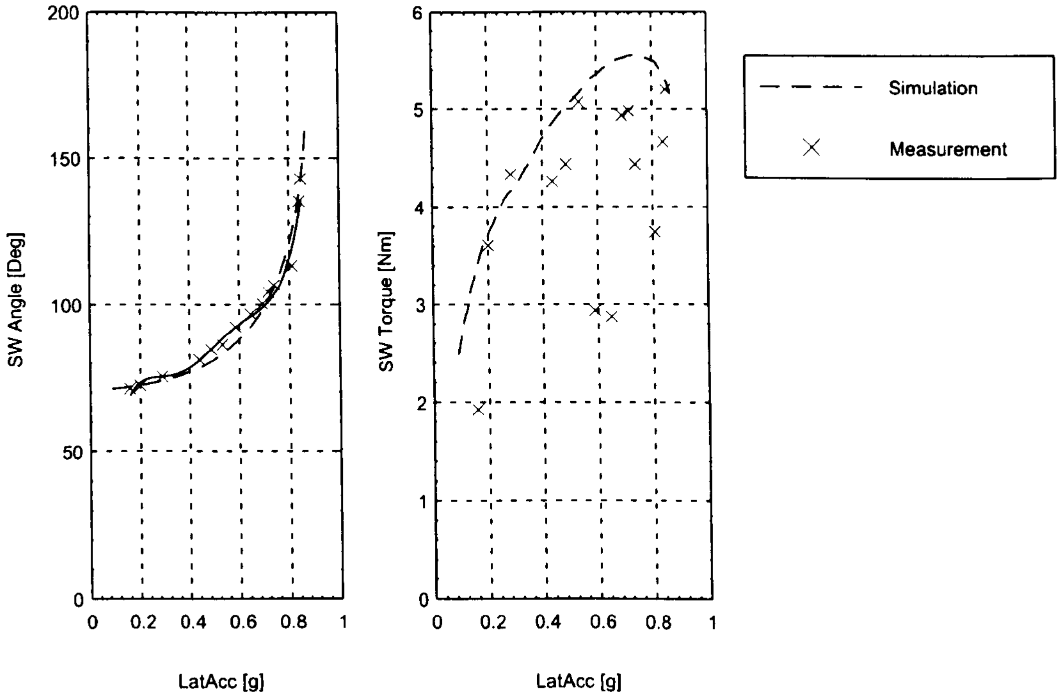

Figure 5.26: **Maximum Column Friction.** Stationary Circle Test Simulation - Radius = 40 m, Left.

Effect of Extra Rack Friction

Unlike the column friction, the rack friction showed little influence on the outcome of the circular test. In figure 5.28, it is also apparent that the rack friction affects the model to a similarly low degree.

Effect of Extra Power Assistance

The range of lateral accelerations from low to severe cornering speeds is covered by the stationary circular test. The hydraulics of the power assistance are in operation through this entire range. Therefore, the full effect of the extra assistance can be observed in this test. As in the test manœuvre, the model produces much lower torque levels with a smaller torque drop-off in the near limit region (figure 5.29).

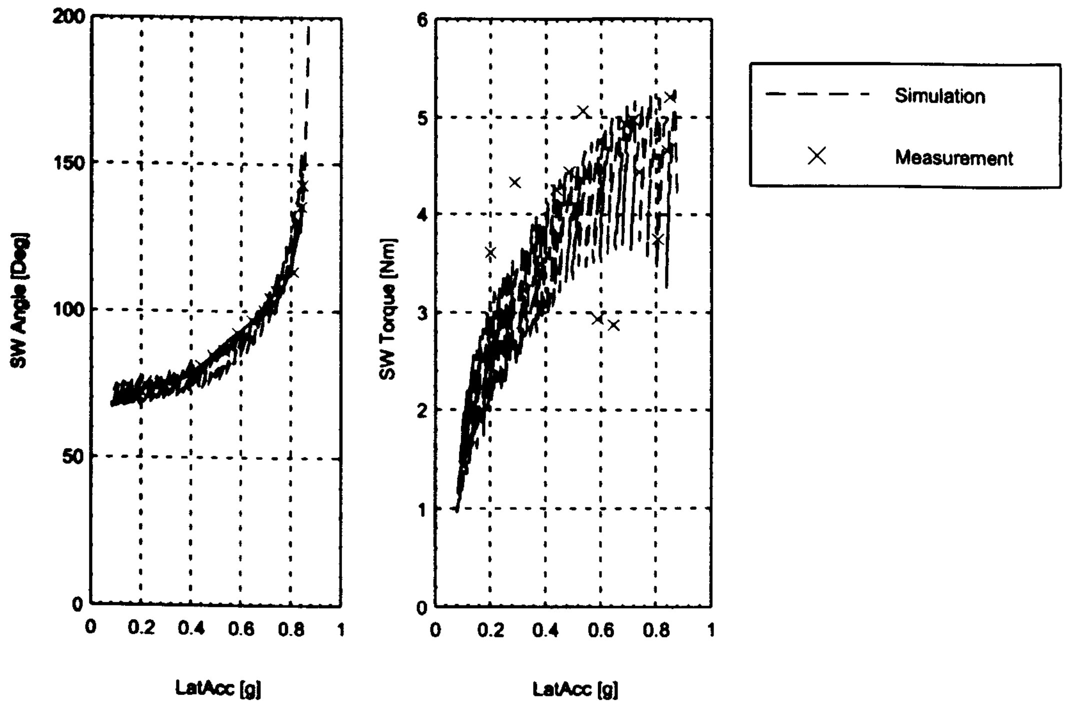

Figure 5.27: **Maximum Column Friction with 4° wobble**. Stationary Circle Test Simulation - Radius = 40 m, Left.

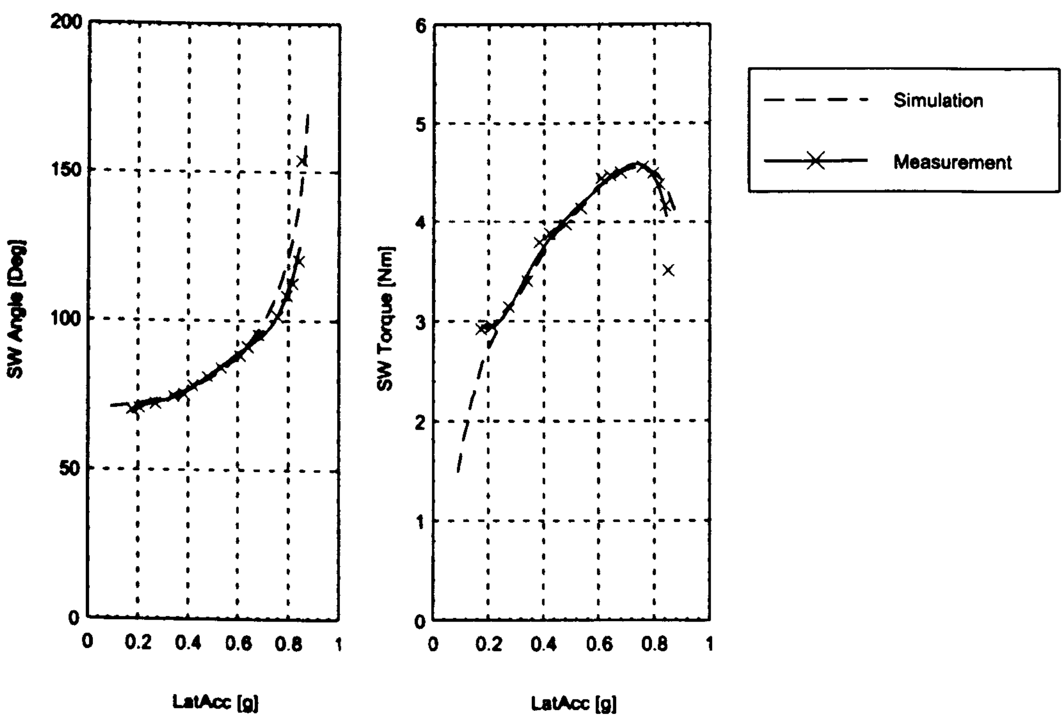

Figure 5.28: **Maximum Rack Friction**. Stationary Circle Test Simulation - Radius = 40 m, Left.

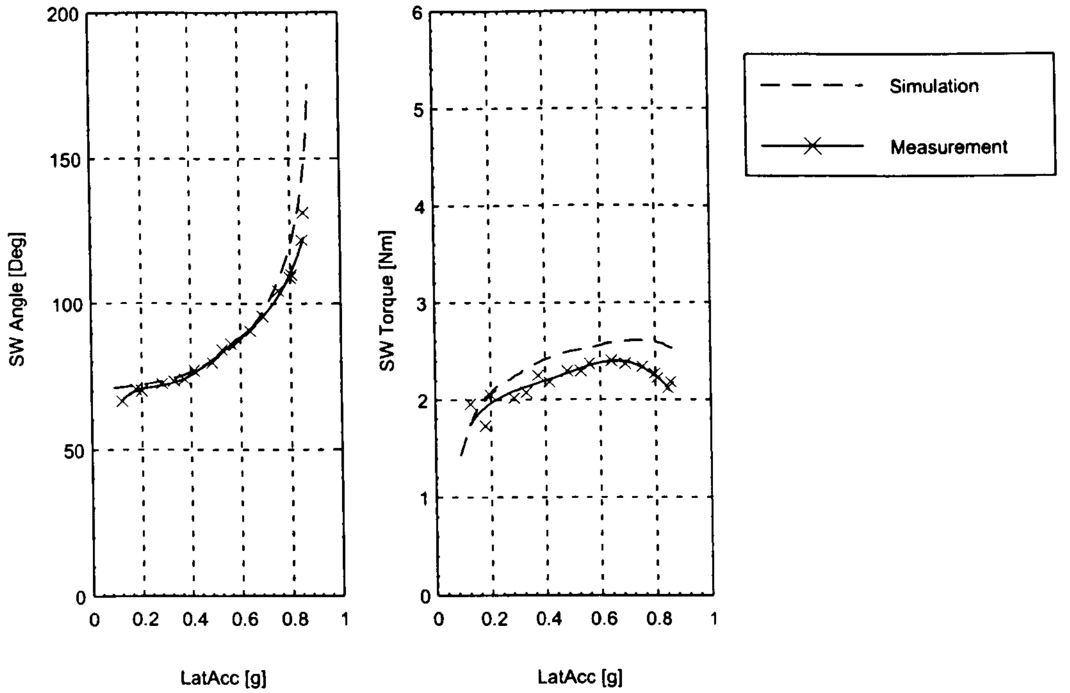

Figure 5.29: **Maximum Power Assistance**. Stationary Circle Test Simulation - Radius = 40 m, Left.

Effect of Extra Free Play

The circular test was not used for the assessment of the effects of free play, as mentioned in section 4.4.5. The play would have no effect on the measured parameters in the test and that is also the case in the simulation.

Chapter 6

Discussion and Analysis

6.1 The Hypothesis

It has been postulated in chapter 2 that steering quality and feel are based on certain features of the input/output relationships of the vehicle system. The relationships with which we are concerned are detailed in table 6.1 and the features which are postulated to describe the quality of these relationships are laid out in table 6.2. These two tables are based on the arguments set out in the hypothesis (chapter 2) and the method of analysis in section 4.2.6.

Vehicle reaction to steering angle input	
Input	*Output*
Steering wheel angle	Lateral acceleration
Steering wheel angle	Yaw rate
Vehicle reaction to steering torque input	
Input	*Output*
Steering wheel torque	Lateral acceleration
Steering wheel torque	Yaw rate
Steering wheel torque	Steering wheel angle

Table 6.1: Relationships examined in the experiment

As seen in table 6.1, the relationships are broken up into two groupings. The vehicle response to steering angle input and its response to steering torque input. The evidence of the features in table 6.2 found in the measured relationships in table 6.1 are outlined in table 6.3. When examining the results of the control experiment, it is the terms in table 6.3 which are examined in detail, as these are postulated to describe the quality of the system.

Feature	Evidence in Relationships
Correlation	Proximity to linear (perfectly correlated) case.
	Lack of deadbands.
Consistency	Ratios of gradients at different operational points.
	Proximity to ideal linear case.
Continuity	Ratios of gradients at different operational points.
	Proximity to ideal linear case.
Single-valuedness	Lack of deadbands - hysteresis.
Progressiveness	Proximity to ideal linear case.
Tyre Information	Torque drop-off near limit.

Table 6.2: Features examined when plotting input vs. output

6.2 Contribution of Testing

Vehicle testing was employed to perform the control experiment by parameter variation described in section 2.5. These parameters were chosen because it was postulated that they would affect the relationships in table 6.1 and thus the quality of the steering system. The full results of all the tests are set out in section 4.4.

Table 6.3 shows which features of the measurements are affected by this control quality experiment. These terms have been argued as affecting quality. They include all the results from the transition test reported in section 4.4 and all the results from the circular test. The weave test produces many terms described by Norman [1984] and Farrer [1993] plus some additional terms. Table 6.3 focuses on those terms postulated to describe steering quality according to the hypothesis, namely the deadband and ratio terms. The measurements of these terms from section 4.4 are consolidated and reproduced in the following figures 6.1 to 6.5.

These results from the weave test, along with the transition test and circular test results, will be discussed in relation to their overall contribution to the experiment in the following section, which details the correlation of subjective and objective results.

Vehicle reaction to steering angle input	
Input	*Output*
Steering wheel angle	**Lateral acceleration**
Weave Test:	
Gradient ratio:	Steering compliance effect
Deadband:	Acceleration deadband
Transition Test:	
Proximity to linear case	
Input	*Output*
Steering wheel angle	**Yaw rate**
Weave Test:	
Gradient ratio:	Yaw rate response gain ratio
Deadband:	Response deadband
Transition Test:	
Proximity to linear case	
Vehicle reaction to steering torque input	
Input	*Output*
Steering wheel torque	**Lateral acceleration**
Weave Test:	
Gradient ratio:	Road feel ratio
Deadband:	Coulomb friction deadband
Transition Test:	
Proximity to linear case	
Circular Test:	
Tyre Information:	Torque drop-off near limit
Input	*Output*
Steering wheel torque	**Yaw rate**
Transition Test:	
Proximity to linear case	
Input	*Output*
Steering wheel torque	**Steering wheel angle**
Weave Test:	
Gradient ratio:	Steering stiffness ratio
Deadband:	Torque deadband
Transition Test:	
Proximity to linear case	

Table 6.3: Quantities from measurements which describe the features in table 6.2

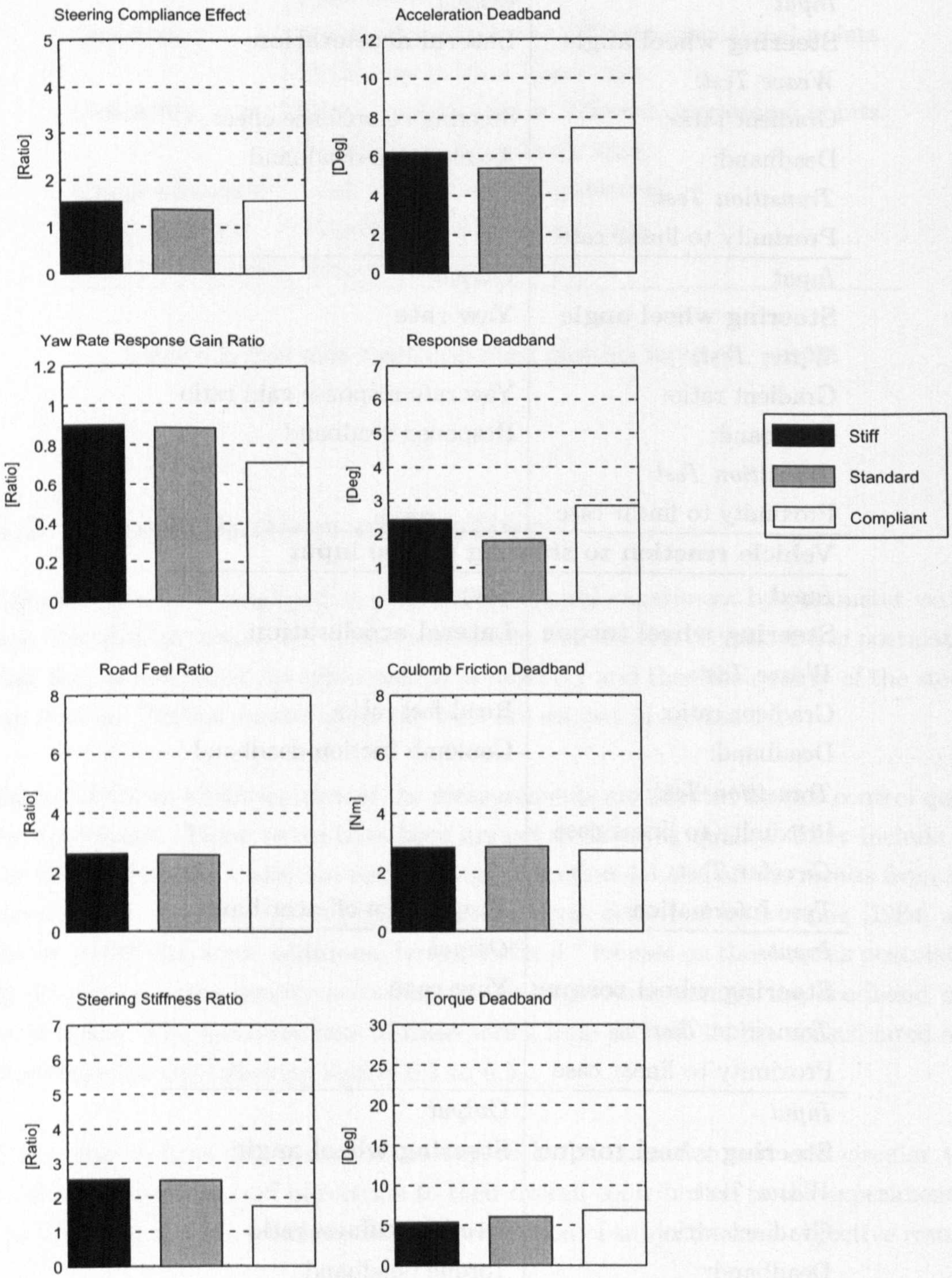

Figure 6.1: Weave test condensed characteristic values - Compliance variation.

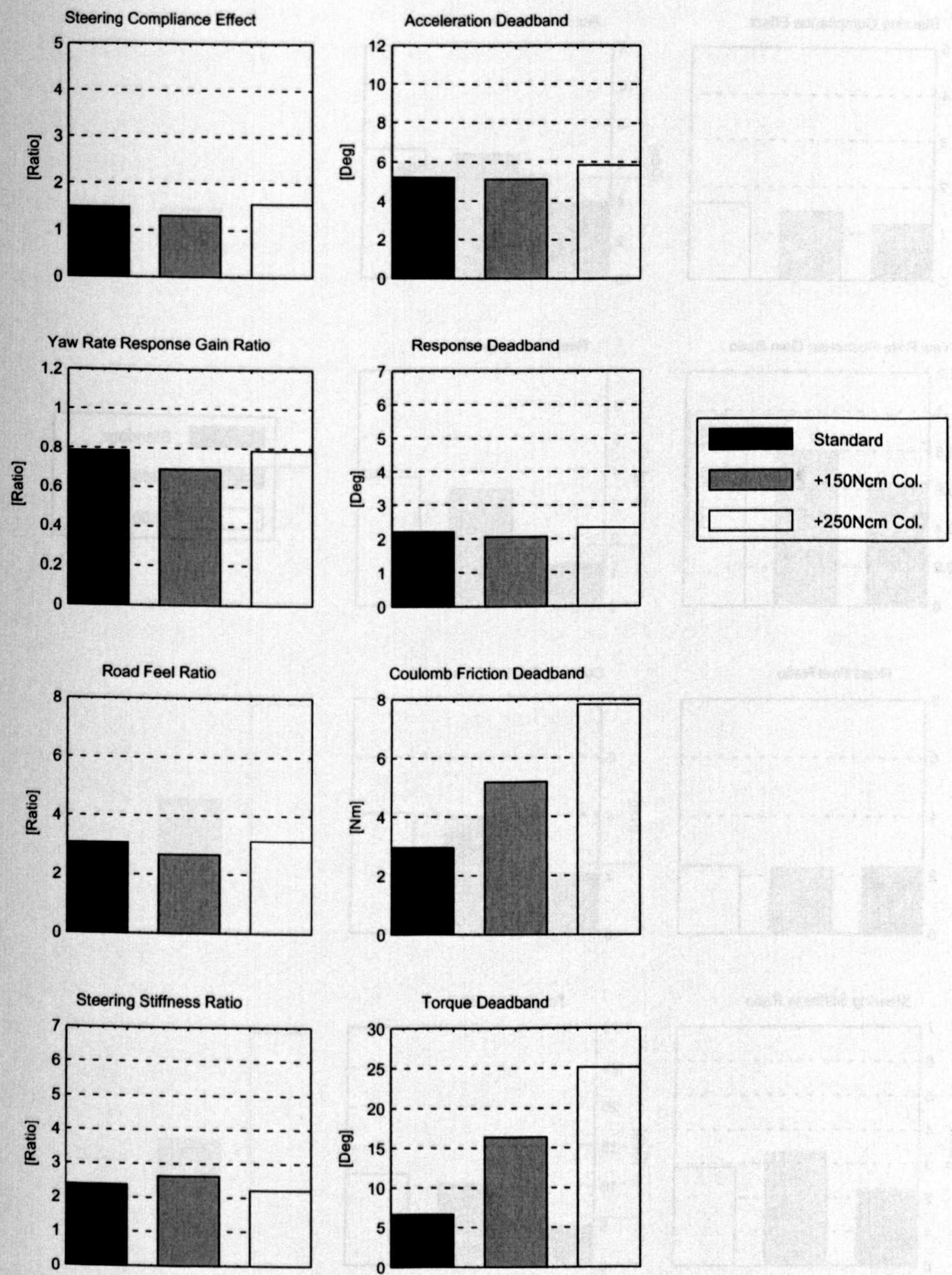

Figure 6.2: Weave test condensed characteristic values - Column friction variation.

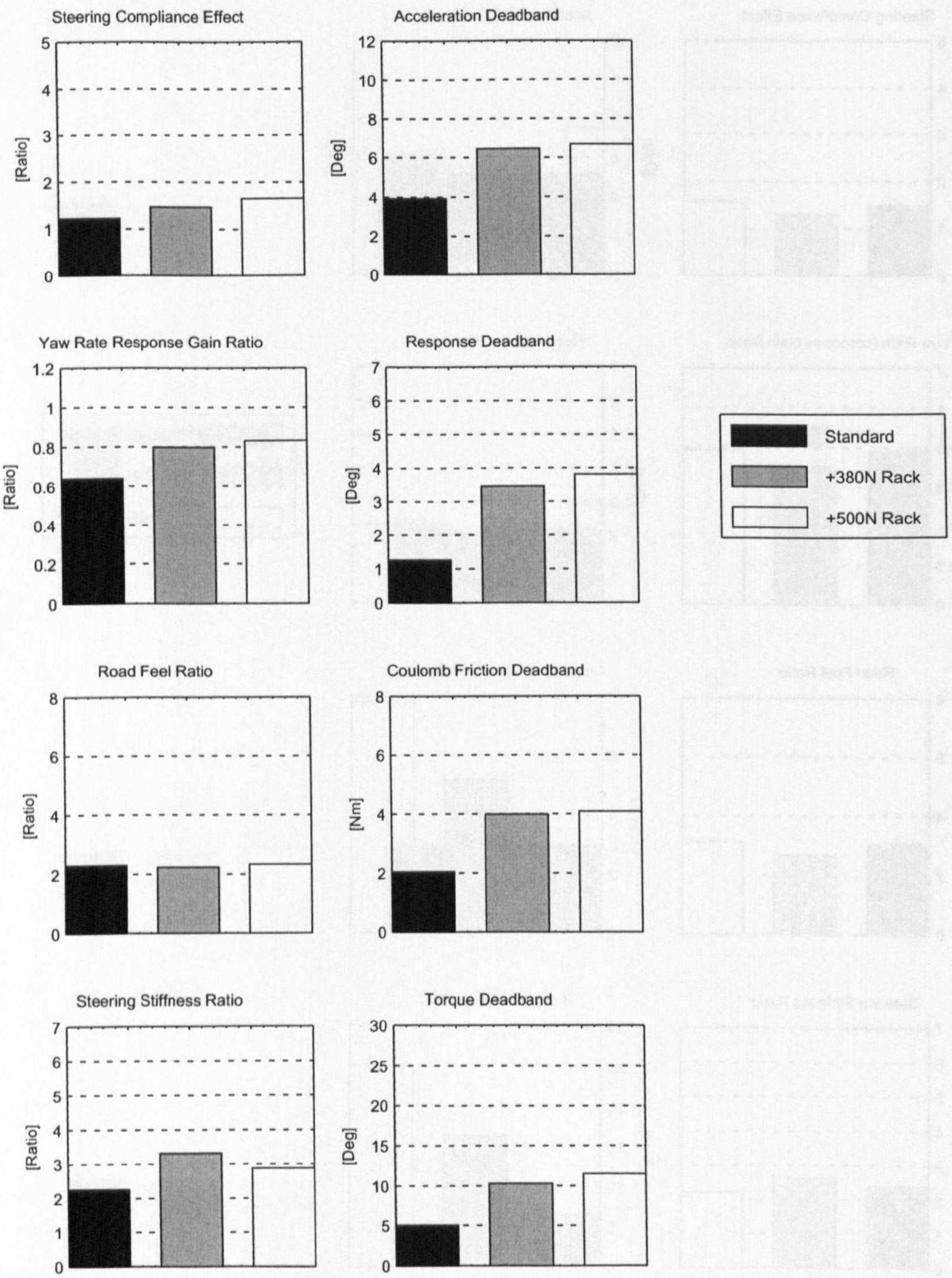

Figure 6.3: Weave test condensed characteristic values - Rack friction variation.

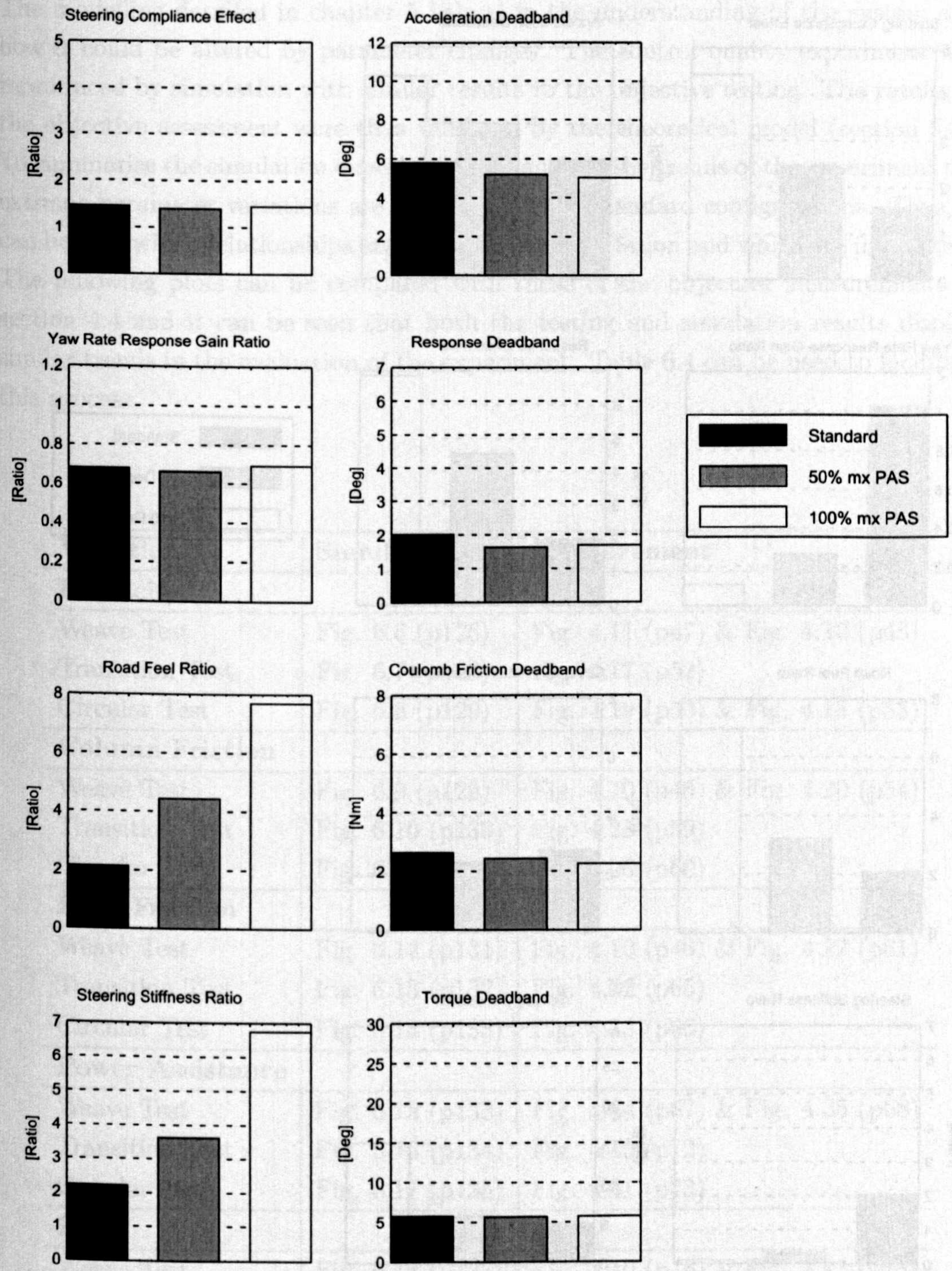

Figure 6.4: Weave test condensed characteristic values - Power assistance variation.

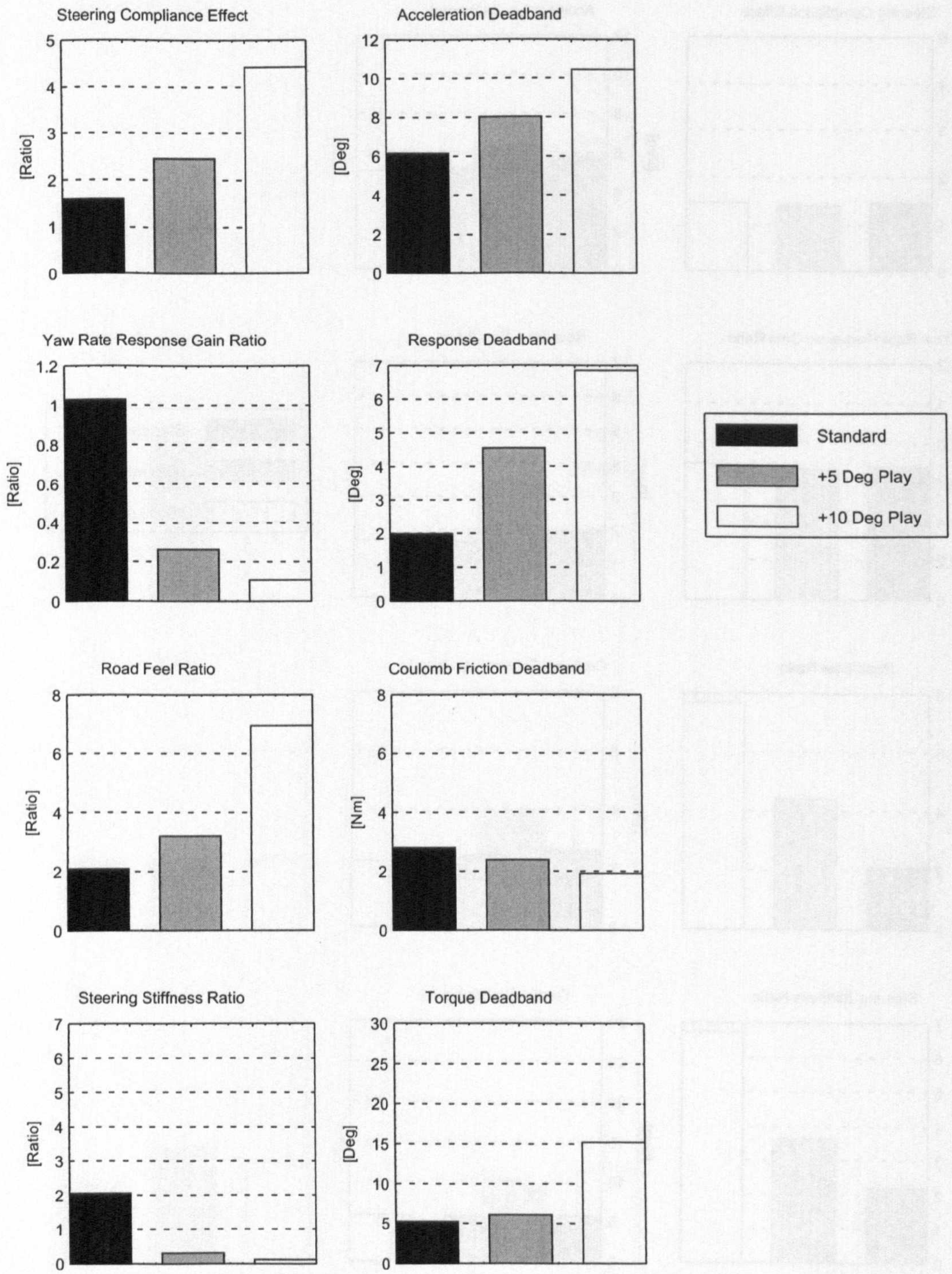

Figure 6.5: Weave test condensed characteristic values - Play variation.

6.3 Contribution of Simulation

The modelling detailed in chapter 5 helped in the understanding of the system and how it could be altered by parameter changes. The control quality experiment was reproduced by simulation with similar results to the objective testing. The results of the objective assessment were thus validated by the theoretical model (section 5.3). To summarise the simulation experiment and analyse the trends of the experiment the extreme parameter variations are plotted with the standard configurations. Thus, it can be seen which relationships are sensitive to the variation and which are insensitive. The following plots can be compared with those of the objective measurements in section 4.4 and it can be seen that both the testing and simulation results display similar trends in the evaluation of the experiment. Table 6.4 can be used to facilitate this process.

Variation	Simulation	Measurement
Elasticity		
Weave Test	Fig. 6.6 (p126)	Fig. 4.11 (p47) & Fig. 4.12 (p48)
Transition Test	Fig. 6.7 (p128)	Fig. 4.17 (p52)
Circular Test	Fig. 6.8 (p129)	Fig. 4.19 (p53) & Fig. 4.18 (p53)
Column Friction		
Weave Test	Fig. 6.9 (p129)	Fig. 4.10 (p46) & Fig. 4.20 (p54)
Transition Test	Fig. 6.10 (p130)	Fig. 4.25 (p59)
Circular Test	Fig. 6.11 (p131)	Fig. 4.26 (p60)
Rack Friction		
Weave Test	Fig. 6.12 (p131)	Fig. 4.10 (p46) & Fig. 4.27 (p61)
Transition Test	Fig. 6.13 (p132)	Fig. 4.32 (p65)
Circular Test	Fig. 6.14 (p133)	Fig. 4.33 (p66)
Power Assistance		
Weave Test	Fig. 6.15 (p133)	Fig. 4.34 (p67) & Fig. 4.35 (p68)
Transition Test	Fig. 6.16 (p134)	Fig. 4.40 (p72)
Circular Test	Fig. 6.17 (p135)	Fig. 4.41 (p73)
Play		
Weave Test	Fig. 6.18 (p135)	Fig. 4.10 (p46) & Fig. 4.43 (p74)
Transition Test	Fig. 6.19 (p136)	Fig. 4.48 (p78)

Table 6.4: Index for direct comparison of trends from simulation to measurement.

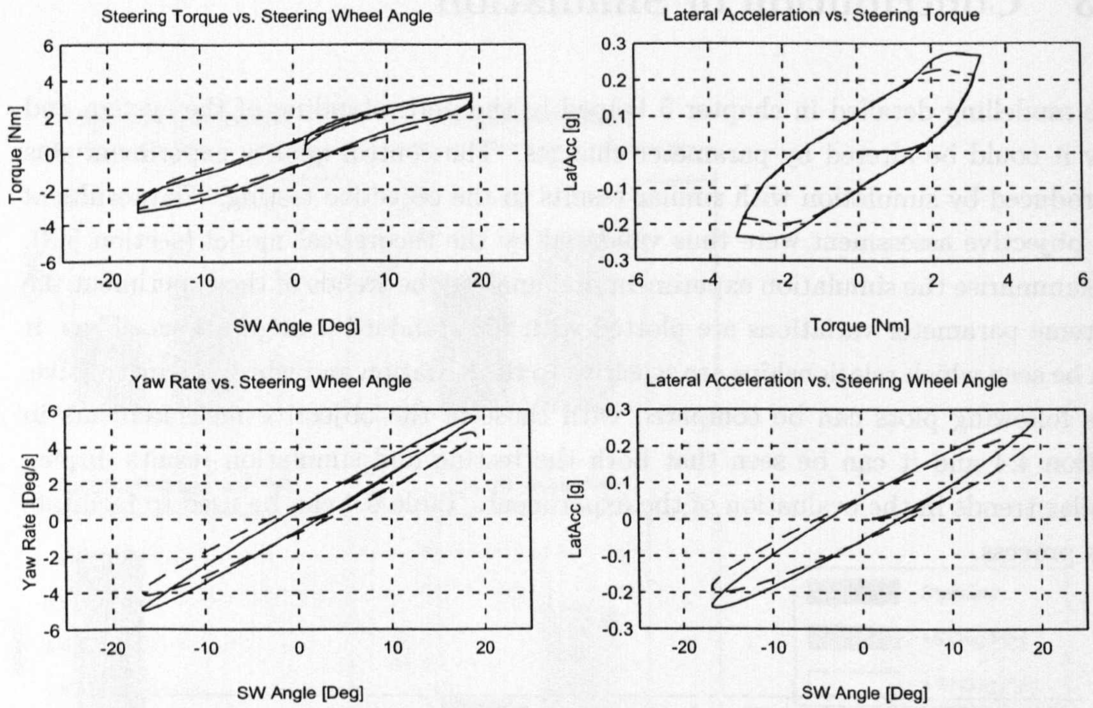

Figure 6.6: Weave test simulation cross plots - Compliance Effect. Stiffest variation - solid line. Most compliant - dashed line.

Effect of Extra Compliance

Figure 6.6 shows how the compliance affects all relationships except for the vehicle lateral reaction to the steering torque. The only difference here is that there is less torque generated at the extremes for the given steering angle. The sensitivity of the lateral reaction to the angle input is further shown in figure 6.7 in the middle row of plots. Again, the vehicle's reaction to steering torque depicted in the third row is only slightly sensitive to the change in elasticity. The circular test simulation (figure 6.8) shows that in the higher range of acceleration the torque/lateral acceleration correlation is not affected, as the two curves are identical and thus appear as one.

Effect of Column Friction

Through all three manœuvres, the simulation produces a consistent result when the column friction is varied. The torque relationships are all severely altered. However, the vehicle's lateral response to steering angle input is completely insensitive to the column friction (figures 6.9, 6.10, 6.11).

Effect of Rack Friction

Varying the rack friction produces a similar alteration to the steering torque plots as does the variation of friction at the steering column(figures 6.12, 6.13). However, figure 6.14 shows no change to the torque levels as levels of lateral acceleration increase past the on-centre region. The increase in torque required is fully compensated by the power assistance here. The response to the angle input is also slightly altered in the on centre region. This is evident from figures 6.12 and 6.13 where the curves relating steering angle to lateral acceleration and yaw rate are not exactly identical.

Effect of Power Assistance

The power assistance variation is another where the vehicle's directional response to a steering angle input is rather insensitive. In figure 6.15 there is no change in the steer angle/lateral acceleration and yaw rate relation. However, figure 6.16 shows a very slight change in the vehicle response to the steer angle input, which was barely noticeable in the measurements. This is because the system requires less torque and thus the elastic components are deflected less. It is the reverse effect of the steering rack friction. The torque levels are, as seen before, reduced, with extra assistance. This is clearly evident looking at the torque relationships in figures 6.15, 6.16 and 6.17.

Effect of Free Play

Figure 6.18 shows that all the weave test hysteresis results are affected by the clearance added to the system. The vehicle reaction to the torque input is insensitive to the play in the transition test (figure 6.19) while in the weave test there is an effect, due to the changes of direction of the steering wheel.

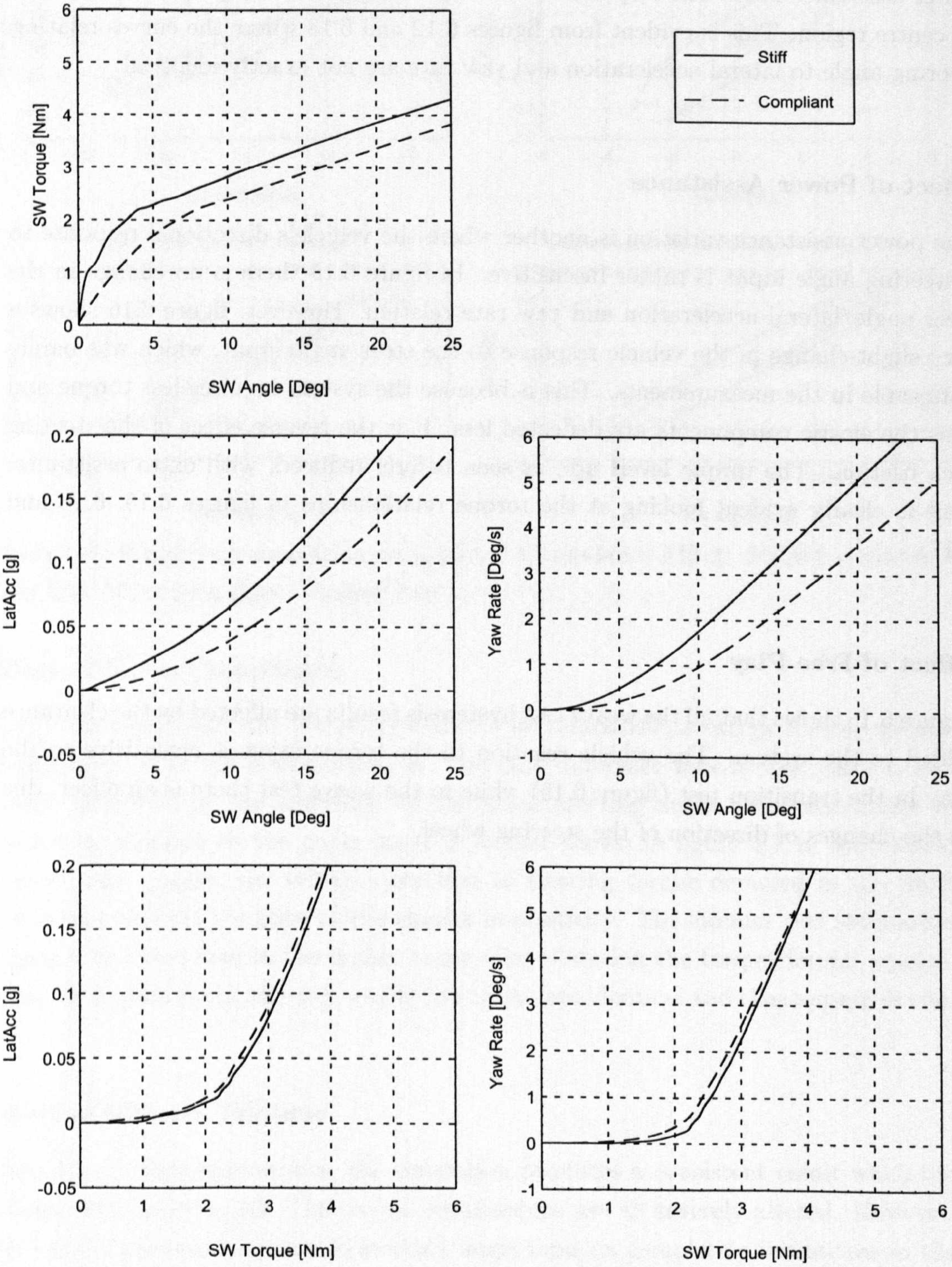

Figure 6.7: Transition test simulation - Compliance Effect.

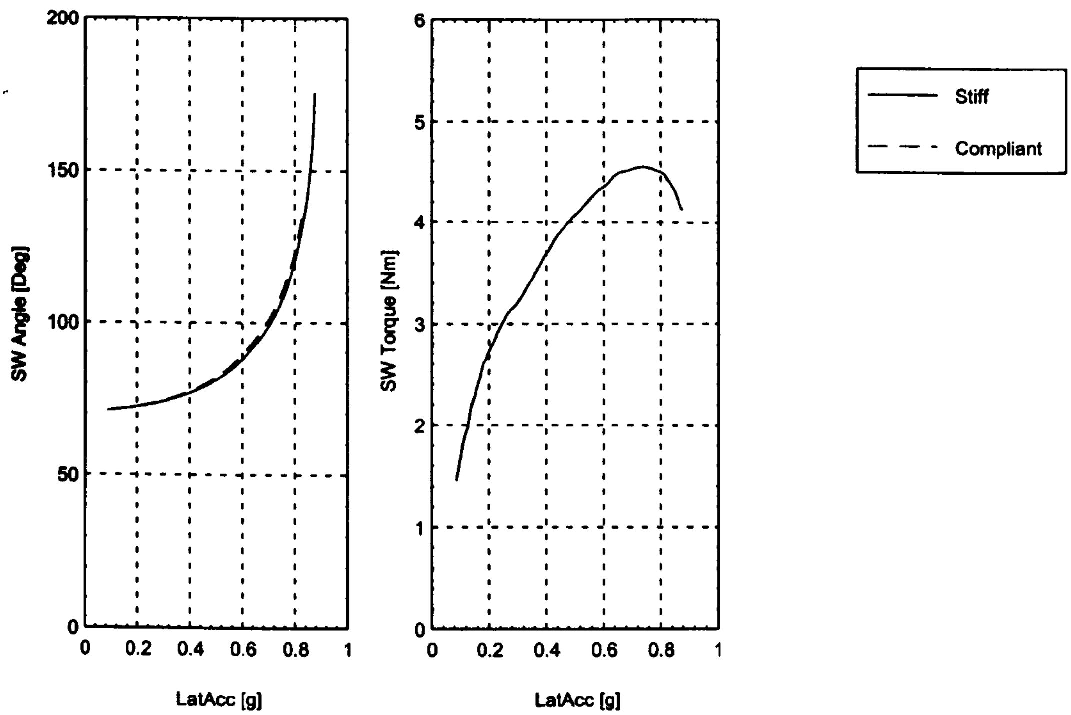

Figure 6.8: Stationary circle test simulation - Radius = 40 m, Left. Compliance Effect.

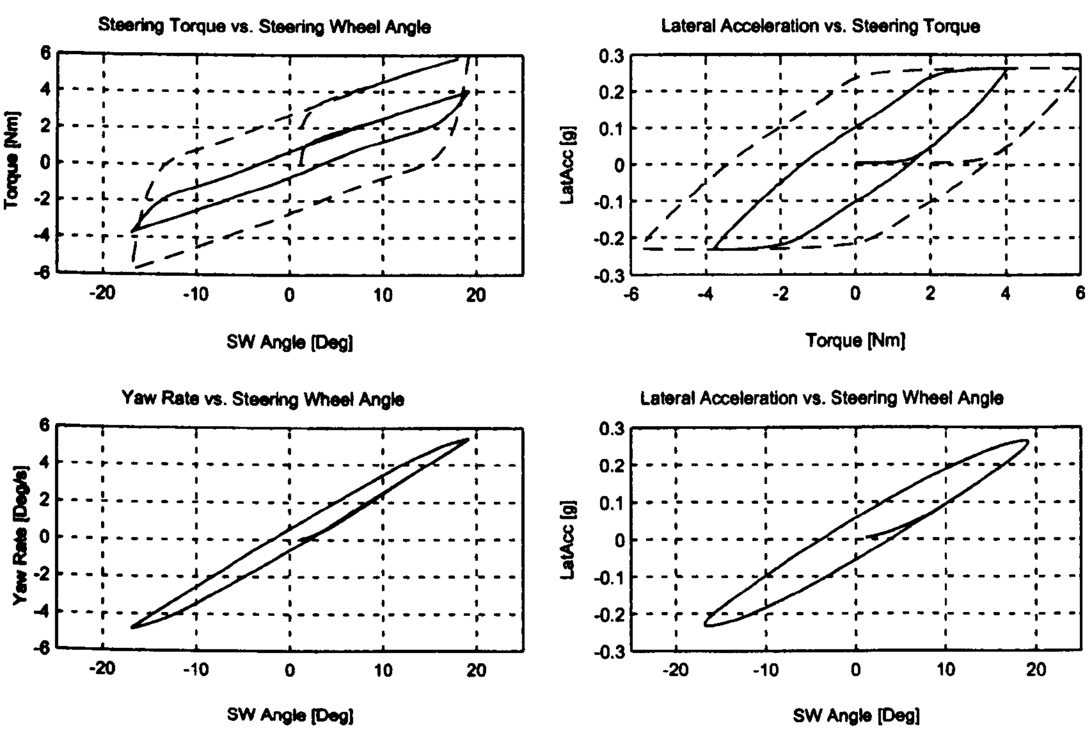

Figure 6.9: Weave test simulation cross plots - Column Friction Effect. Standard - solid line. Maximum column friction - dashed line.

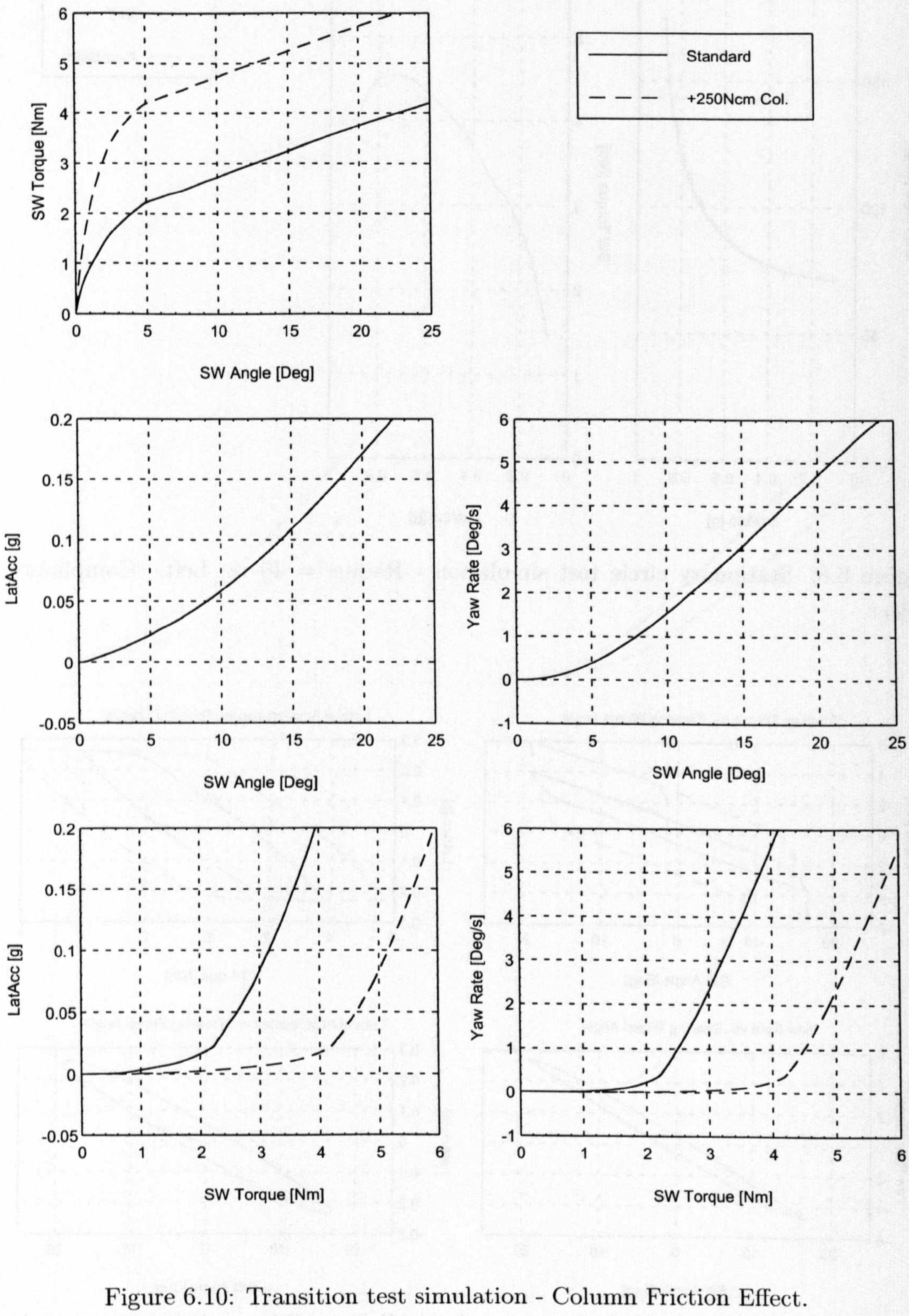

Figure 6.10: Transition test simulation - Column Friction Effect.

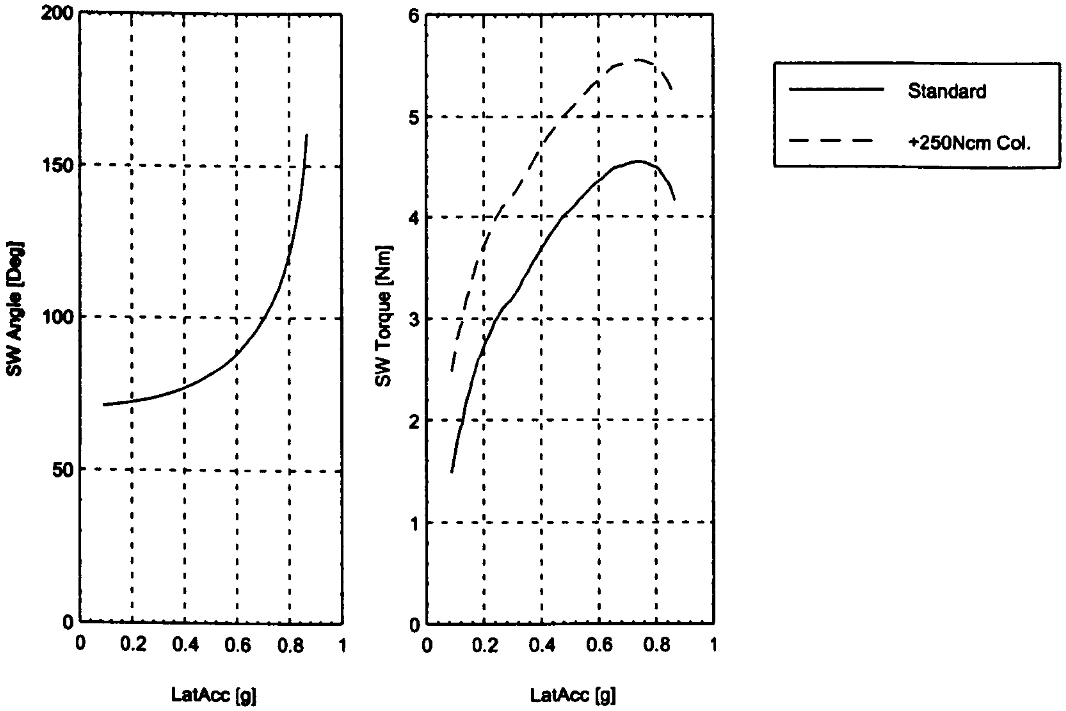

Figure 6.11: Stationary circle test simulation - Radius = 40 m, Left. Column Friction.

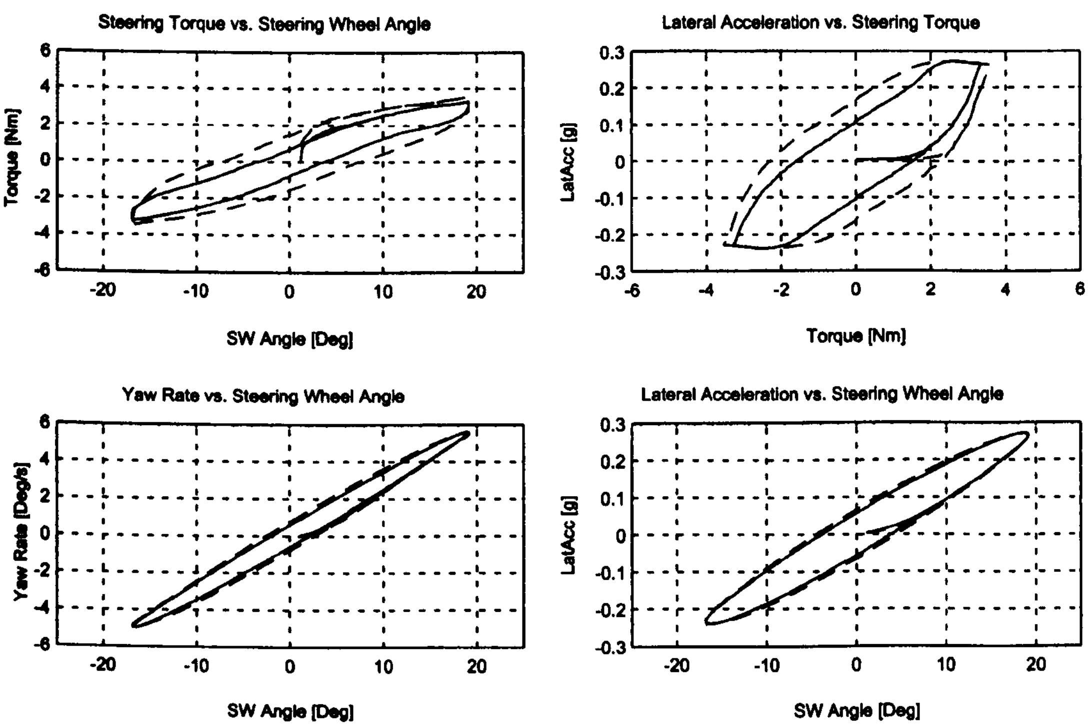

Figure 6.12: Weave test simulation cross plots - Rack Friction Effect. Standard - solid line. Maximum rack friction - dashed line.

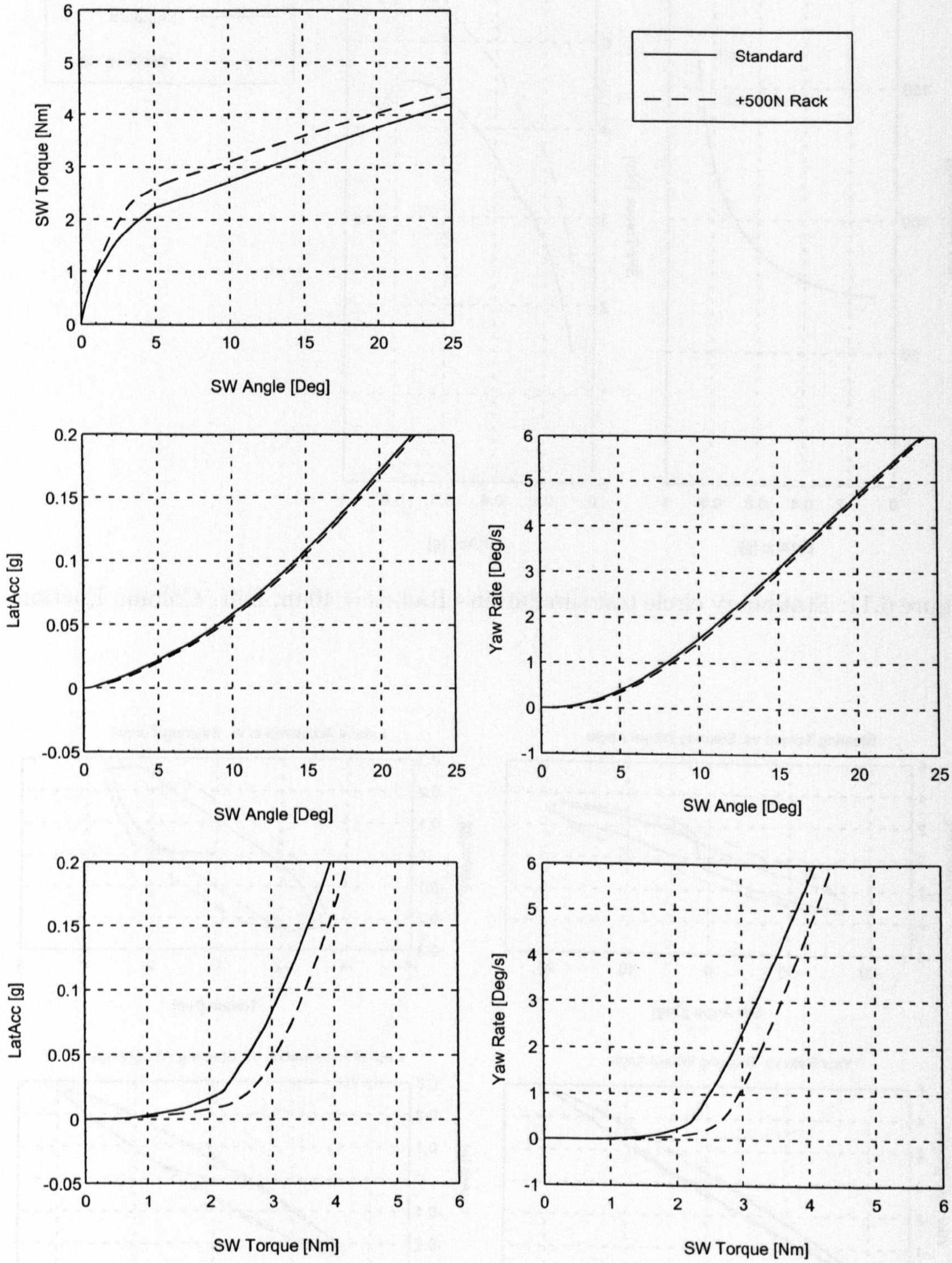

Figure 6.13: Transition test simulation - Rack Friction Effect.

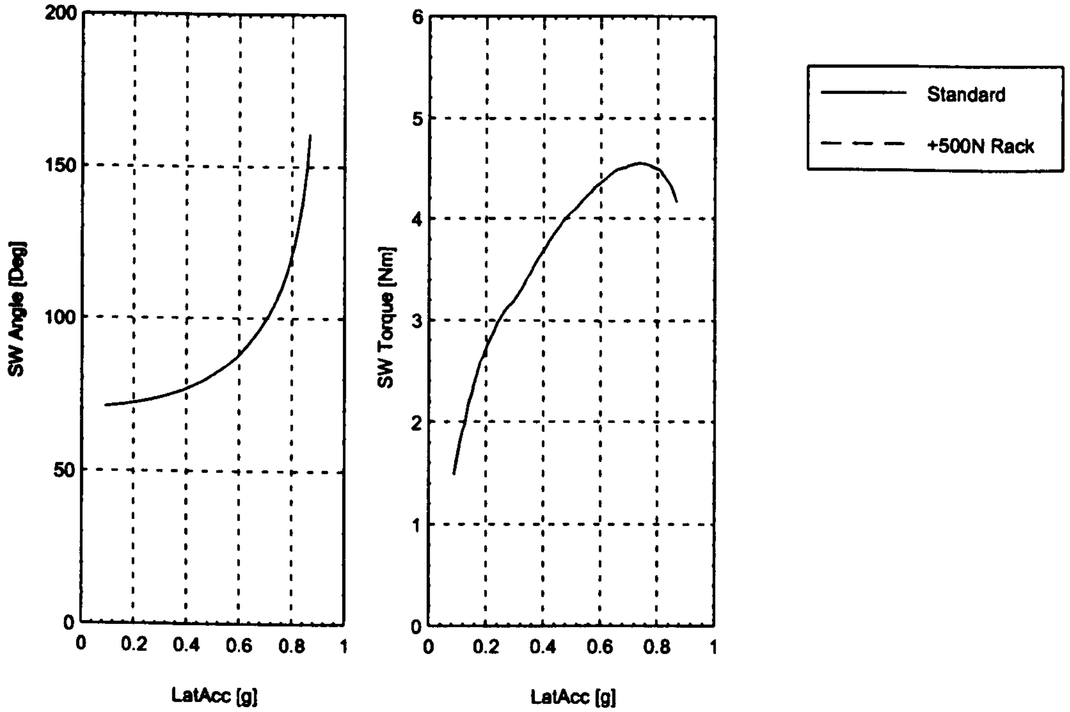

Figure 6.14: Stationary circle test simulation - Radius = 40 m, Left. Rack Friction.

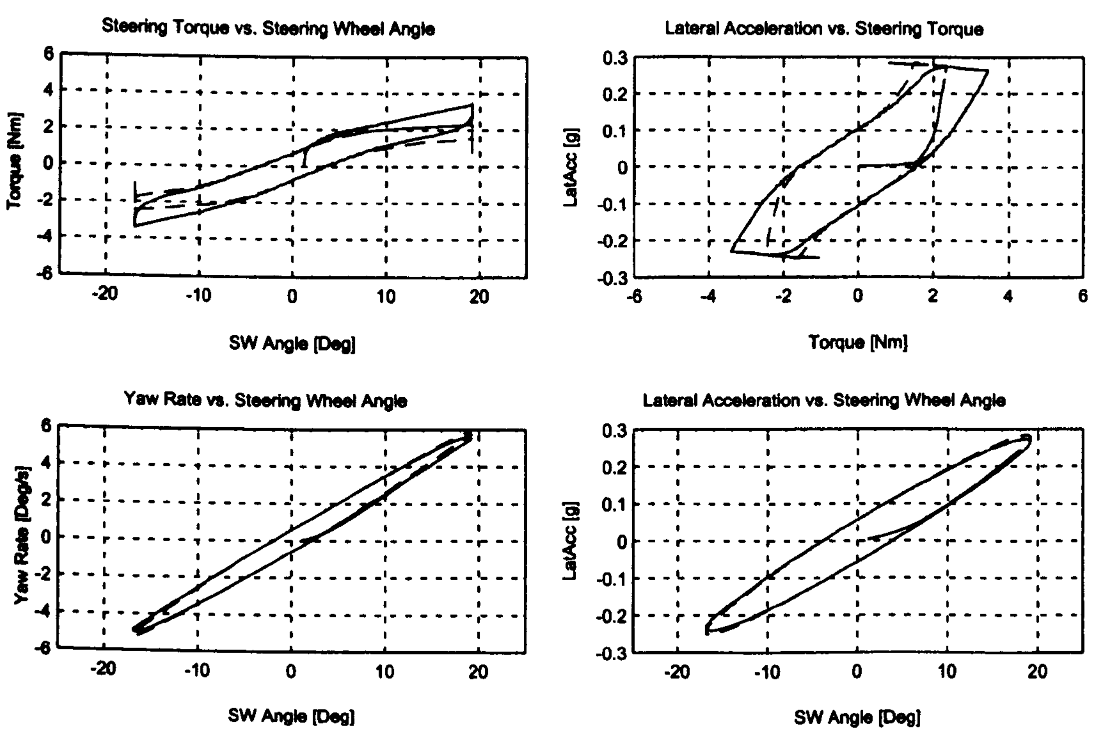

Figure 6.15: Weave test simulation cross plots - Power Assistance Effect. Standard - solid line. Maximum Assistance - dashed line.

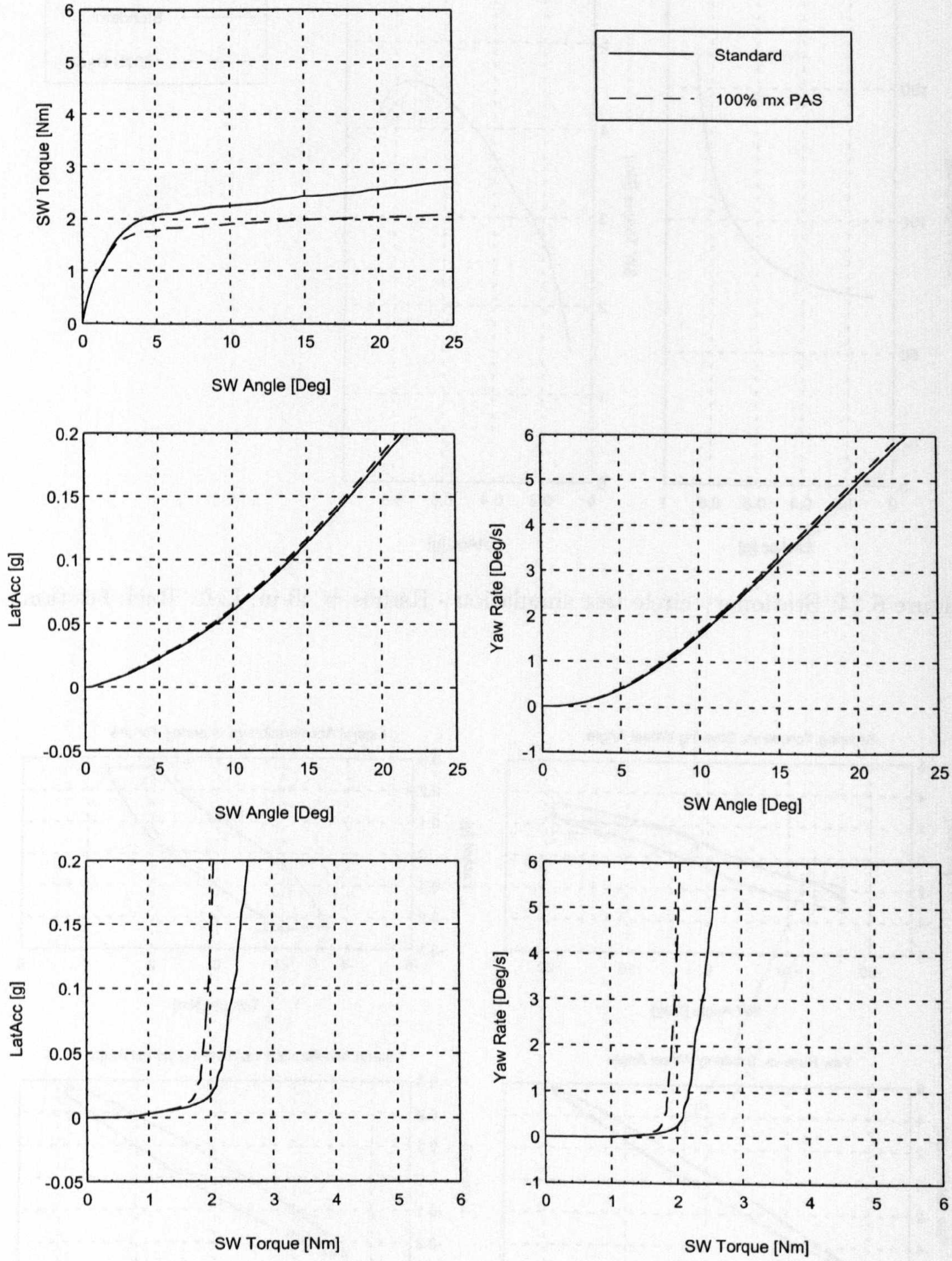

Figure 6.16: Transition test simulation - Power Assistance Effect.

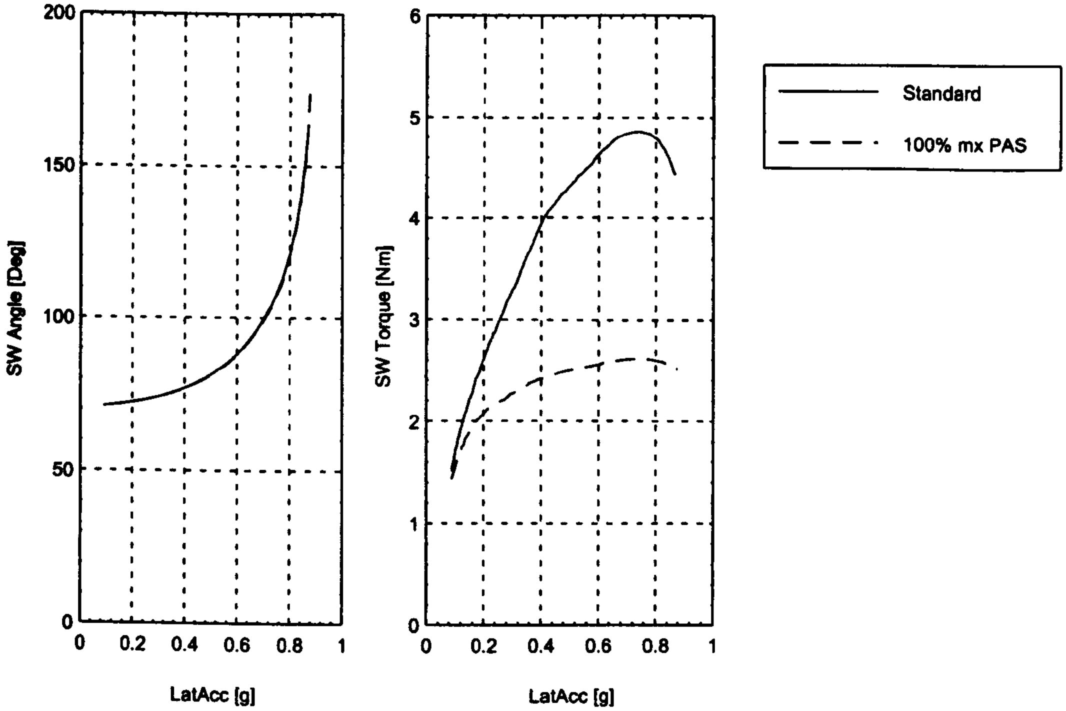

Figure 6.17: Stationary circle test simulation - Radius = 40 m, Left. Power Assistance.

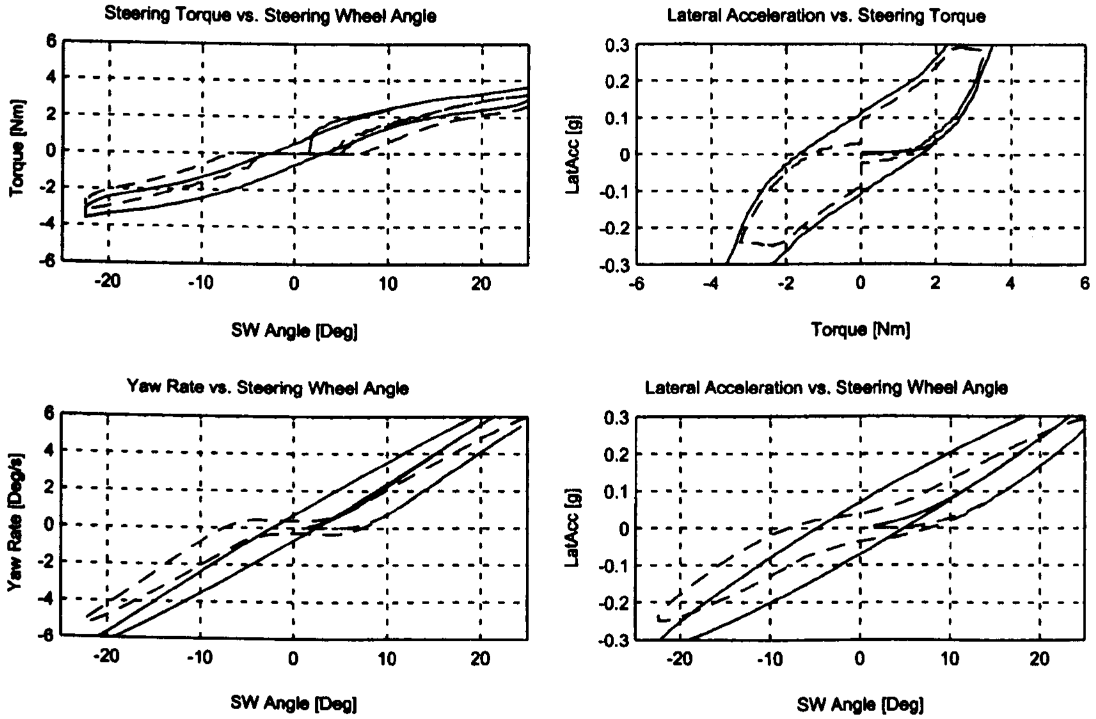

Figure 6.18: Weave test simulation cross plots - Free Play Effect. Standard - solid line. Maximum Assistance - dashed line.

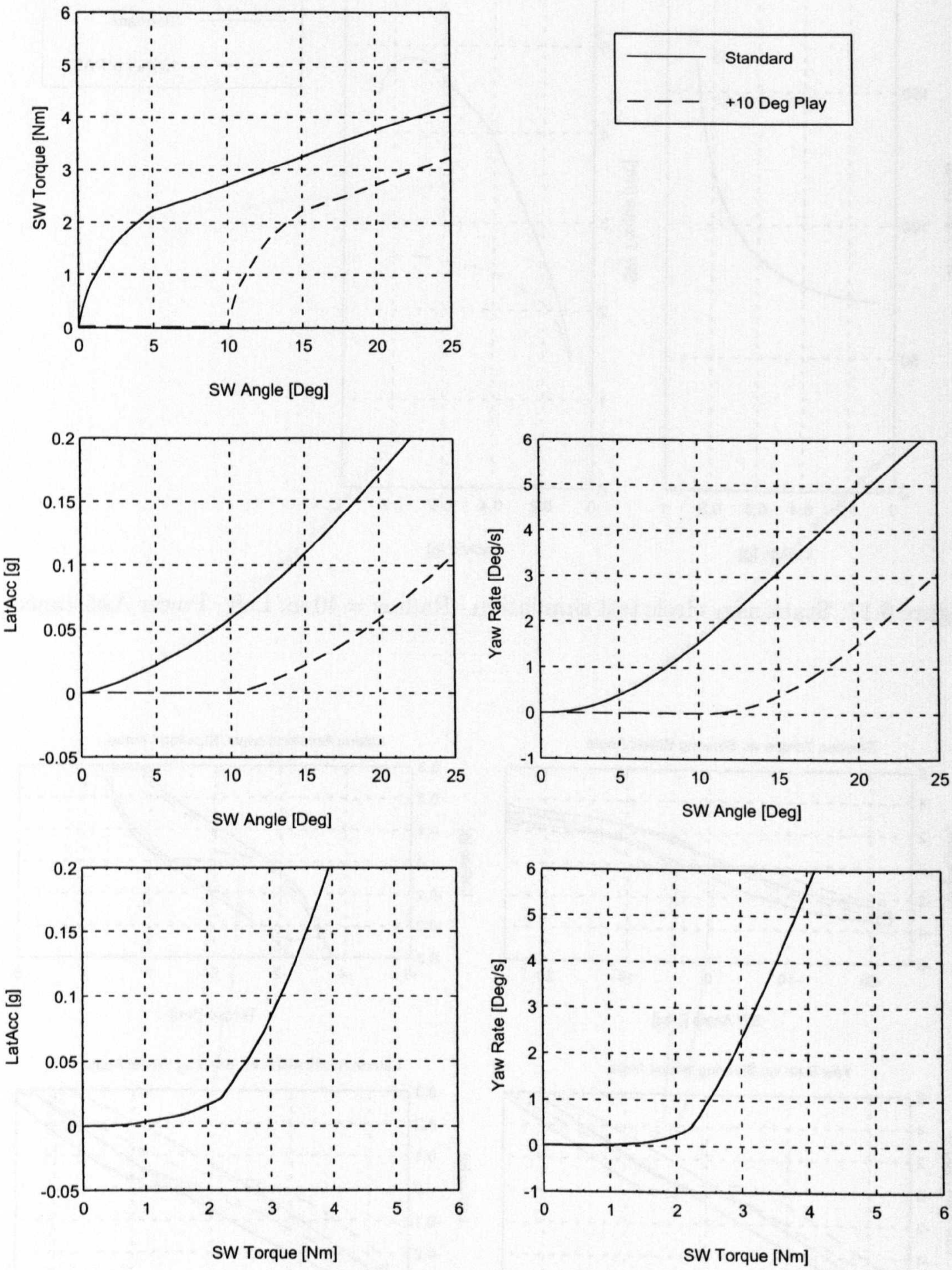

Figure 6.19: Transition test simulation - Free Play Effect.

6.4 Correlation of Subjective and Objective Results

The experiments have shown that alterations in the vehicle's properties can be measured objectively. It has further been postulated that the measured quantities describe the steering quality. As seen in section 4.5, the experiments were both performed and subjectively evaluated by an expert test driver. From this, we obtain a picture of how the driver's perception of quality has altered as the vehicle's properties have been changed. By correlating this evaluation with the objective assessment hypothesised to describe this alteration of quality, the accuracy of the objective evaluation can be assessed.

The subjective evaluations and objective measures to be correlated are listed in tables 6.5, 6.6 and 6.7. The correlation is drawn according to table 6.5 for the terms relating to the reaction to a steering angle input, table 6.6 for terms relating to the reaction to a torque input, and table 6.7 which describes the vehicle behaviour in the high lateral acceleration range.

Subjective Terms (Scores from Questionnaire)	
Agility	on-centre
	at mid a_y
	at high a_y
Steering wheel angle required	on-centre
	at mid a_y
	at high a_y
Objective Terms	
Weave Test (Char. Values)	*Transition Test (Deviation from Linear)*
Compliance effect	Lateral acceleration vs. Steering wheel angle
Acceleration deadband	Yaw rate vs. Steering wheel angle
Yaw rate ratio	
Response deadband	

Table 6.5: Terms to be correlated for the reaction to steering angle input.

The correlation between the subjective and objective evaluations is presented graphically (figures 6.21 to 6.34). The subjective scores from section 4.5.4 have been normalised. The standard configuration is taken as 100 % . The scores for the variations are then taken as a percentage of the standard score and result in figures larger than 100, if the score has increased, and lower than 100, if the score has decreased. In the case of the elasticity variations, the stiffest configuration is taken

Subjective Terms (Scores from Questionnaire)	
Feedback/ Steering Feel	on-centre
	at mid a_y
	at high a_y
Steering wheel torque	on-centre
	at low a_y
	at high a_y
Steering wheel torque gradient	on-centre
	at low a_y
	at high a_y
Objective Terms	
Weave Test (Char. Values)	*Transition Test (Deviation from Linear)*
Road feel ratio	Steering wheel angle vs. Steering wheel torque
Coulomb friction deadband	Lateral acceleration vs. Steering wheel torque
Steering stiffness ratio	Yaw rate vs. Steering torque
Torque deadband	

Table 6.6: Terms to be correlated for the reaction to steering torque input.

as the basis and the standard and compliant variations are expressed as deviations from this. Thus, the three variations are presented in order of increasing compliance; stiff, standard, compliant. The percentages are displayed on the positive y-axes and compliance/friction/servo-assistance/play is increased along the positive x-axis.

Each line denotes the score of a particular feature and is annotated by a legend. The legend terms are in abbreviated form, with the corresponding full terms in table 6.8. The terms are split firstly, according to whether they represent the reaction to an angle or torque input. Secondly, the terms which refer to the limit behaviour were split from those describing normal driving conditions. These three groupings were

Subjective Terms (Scores from Questionnaire)	
Predictability near limit	at limit
Safety feel	at limit
Steering wheel torque drop-off	at limit
	progressive
	timing
Objective	
Graphical Representation of the Stationary Circular Test Results	

Table 6.7: Terms to be correlated for the high lateral acceleration range.

further split into terms which describe a physical quantity, for example; steering angle required, and those which describe a more general feature, e.g. agility (table 6.8).

Reaction to steering angle input			**Abbreviated Term**
General	Agility	on-centre	Agil.on cr
		at mid a_y	Agil.mid ay
		at high a_y	Agil.Hi ay
Physical	Steering wheel angle required	on-centre	SWA on cr
		at mid a_y	SWA mid ay
		at high a_y	SWA hi ay
Reaction to steering torque input			
General	Feedback/ Steering Feel	on-centre	FB on cr
		at mid a_y	FB mid ay
		at high a_y	FB hi ay
Physical	Steering wheel torque	on-centre	Trq on cr
		at low a_y	Trq lo ay
		at high a_y	Trq hi ay
Physical	Steering wheel torque gradient	on-centre	Trq gr.on cr
		at low a_y	Trq gr.lo ay
		at high a_y	Trq gr.hi ay
High lateral acceleration region			
General	Predictability near limit	at limit	Predict.
	Safety feel	at limit	Safety
Physical	Steering wheel torque drop-off	at limit	Trq drop-off
		progressive	Trq DO Pro
		timing	Trq DO tim

Table 6.8: Abbreviations for subjective terms used in plots.(a_y refers to Lateral acceleration)

The objective results are represented in a similar fashion; as percentages where 100 % is the standard configuration. However, it is postulated that, as the objective measures such as deadband and non-linearity increase, the quality is reduced. Thus, to represent a reduction in quality as the terms increase, the inverse of the percentage increase is displayed in the graphs. The correlation between the subjective and objective results is therefore evident when both curves are either decreasing or increasing.

The transition test results are the figures denoting the deviation from the linear ideal from section 4.5.4 and the weave test results are those reproduced in the previous section (6.2). The legends for these objective quantities are also abbreviated and this is explained by table 6.9. The stationary circle test results are reproduced straight from section 4.5.4 in the form of their cross plots, where the torque characteristics at near limit conditions can be examined.

Weave Test	**Abbreviated Term**
Reaction to steering angle input	
Compliance effect	Compl.eff
Acceleration deadband	Acc.DB
Yaw rate ratio	YR ratio
Response deadband	Resp.DB
Reaction to steering torque input	
Road feel ratio	RF ratio
Coulomb friction deadband	C.Fric.DB
Steering stiffness ratio	Stif.ratio
Torque deadband	Torque DB
Transition Test	
Reaction to steering angle input	
Lateral acceleration vs. Steering wheel angle	Ay v. SWA
Yaw rate vs. Steering wheel angle	YR v.SWA
Reaction to steering torque input	
Steering wheel angle vs. Steering wheel torque	SWA v. SWT
Lateral acceleration vs. Steering wheel torque	Ay v. SWT
Yaw rate vs. Steering torque	YR v. SWT

Table 6.9: Abbreviations for objective terms used in plots.

Worked Example of Correlation

Figure 6.20 shows the format of the graphical correlation. Graph 1 represents the effect of the variation on the weave test characteristic values. It can be seen that the compliance effect, acceleration deadband and the response deadband values decrease from 100% from left to right as the parameter is varied. These values are normalised and the inverse of the percentage change is displayed representing a decrease in quality here. (Incidentally, the yaw rate ratio increases off the scale). Graph 2 displays the deviation from linear caused by the varied parameter on the transition test relationships of lateral acceleration vs. steering wheel angle and yaw rate vs. steering wheel angle. Again the inverse is displayed denoting an increase in the non-linearity but a *decrease* in quality (according to the hypothesis) as the percentage values decrease. Graphs 3 and 4 show the change in subjective score as a result of the parameter variation. A decrease here denotes a straightforward decrease in the subjective score.

Correlation can be seen between all terms in graph 1 (except yaw rate ratio) with graph 4, where the subjective terms denote a reduction in agility, as both the curves in graph 1 and graph 4 are decreasing. Both objective terms describing the transition test in graph 2 also correlate with the subjective test results in graph 4. These objective terms in graphs 1 and 2 also correlate with the subjective steering angle required on centre (solid line) from graph 3, as it also decreases representing a decrease in quality. The yaw rate ratio term from graph 1 does not correlate with any terms in graphs 3 and 4.

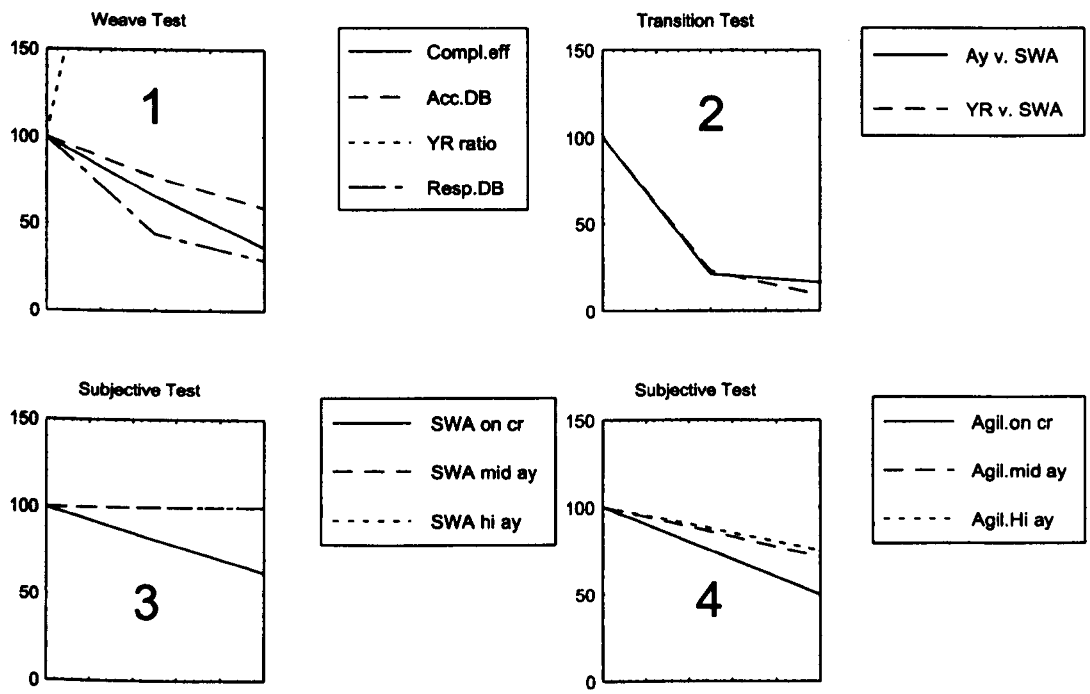

Figure 6.20: **Example Figure - Steering Angle Terms.** Subjective/objective correlation. Y-axes display normalised percentages where 100 = Standard. X-axes show an increase in the parameter varied from left to right.

Compliance Variation Results

Figure 6.21 shows how the steering angle/vehicle reaction relationship changes as more elasticity is introduced into the steering system. It can be clearly seen that the agility decreases subjectively as does the score for the steering angle required. This is expected as the compliance was introduced to affect mainly the vehicle's response to a steering angle, which is reflected here by the agility term. Objectively, little can be drawn from the weave test results but the transition test shows that, directly out of centre, the behaviour is less continuous and this is reflected by the sharp decrease in these terms representing a larger deviation from the linear case. This shows good correlation with the decrease in agility identified by the driver.

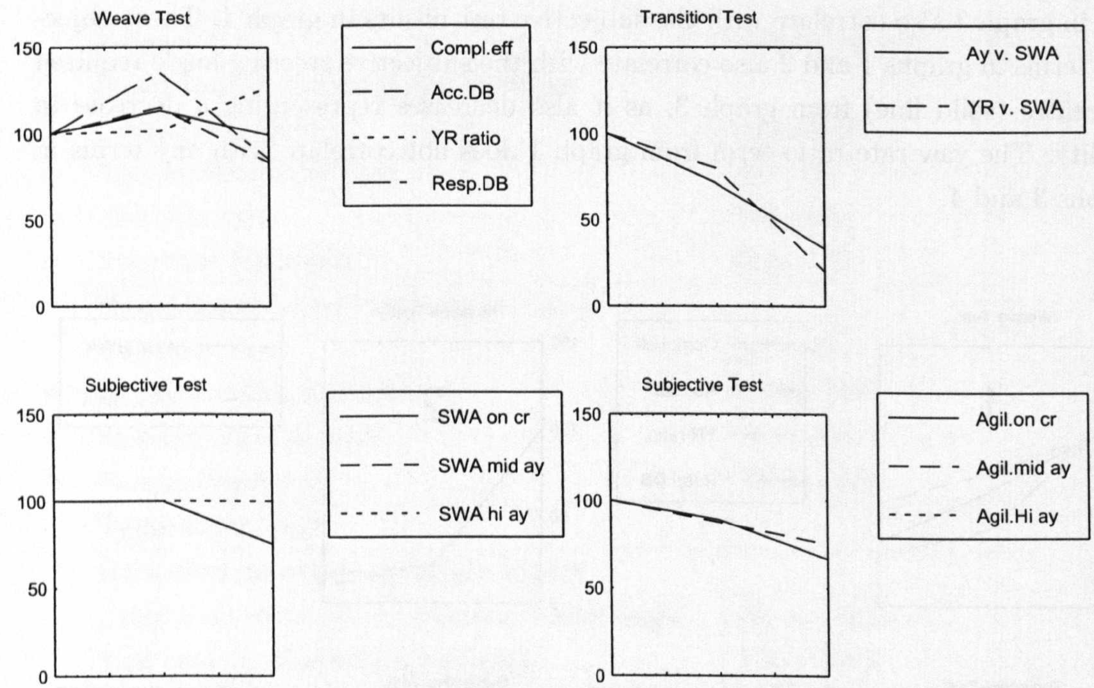

Figure 6.21: **Steering Angle Terms - Compliance Effect.** Subjective/objective correlation. Y-axes display normalised percentages where 100 = Standard. X-axes show an increase in compliance from left to right.

The reaction to the torque input is presented in figure 6.22. Again, the weave test terms demonstrate low sensitivity to this parameter change. The transition test produces a decrease in linearity for the vehicle's lateral reaction to the input. Subjectively, this is reflected by the feedback terms which have suffered and it can be seen that the feedback, or feel, on centre has suffered most. The subjective score for the torque gradient on-centre has decreased most out of the torque gradient terms, all of which show poorer values with increased compliance. The subjective on-centre terms, thus, correlate particularly well with the degradation of the linearity on-centre shown from the transition test.

It was not expected that the near limit behaviour would be much affected by a change in the elasticity in the steering column. From the objective result in figure 6.23 it is evident that this is the case, which is further reinforced by the theoretical result from the model (section 6.3, figure 6.8). However, in the subjective evaluation there is a small difference noted as the safety term decreases, in spite of the terms describing the torque at the limit improving. This must then be attributed to some immeasurable

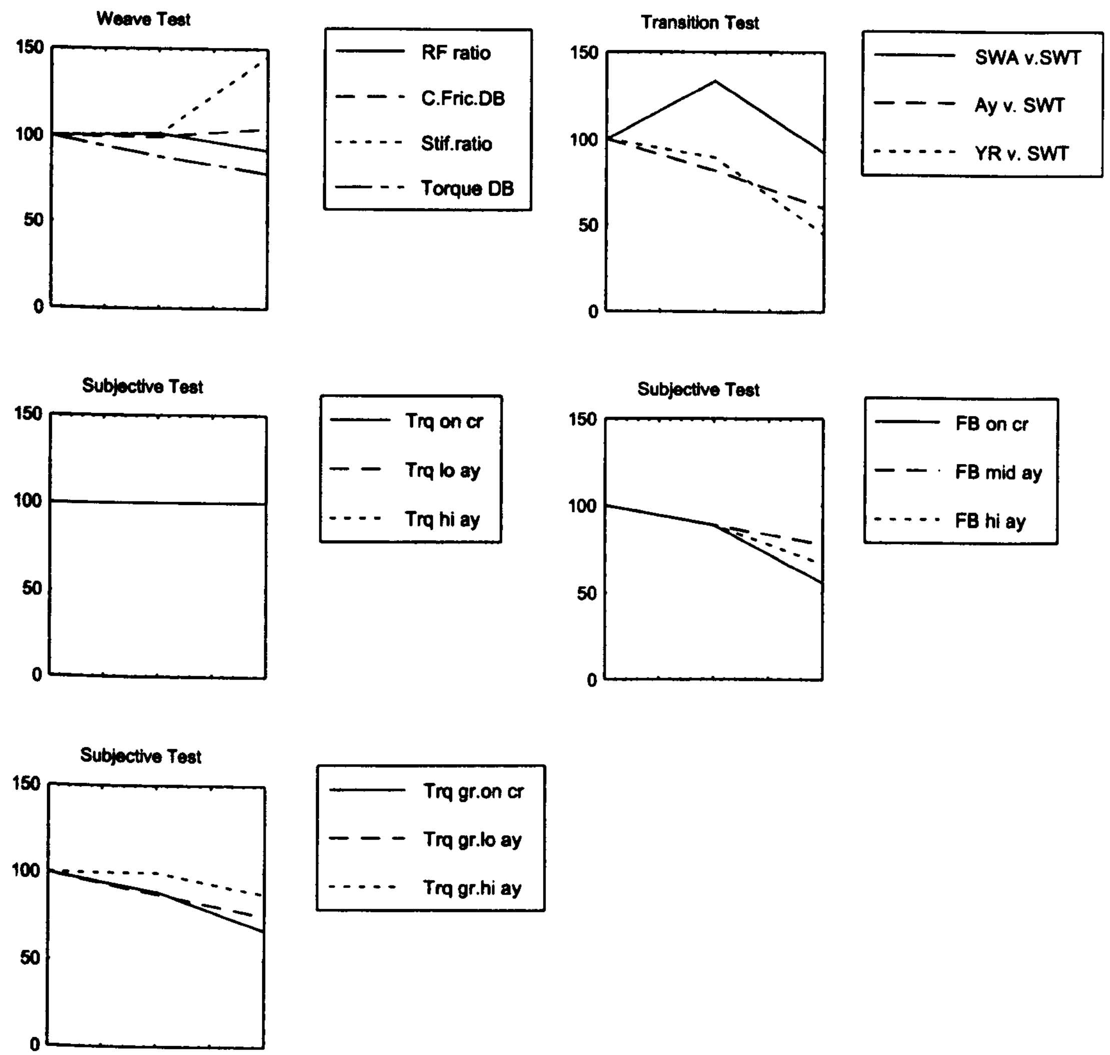

Figure 6.22: **Steering Torque Terms - Compliance Effect**. Subjective/objective correlation. Y-axes display normalised percentages where 100 = Standard. X-axes show an increase in compliance from left to right.

subjective value or an error in the subjective evaluation.

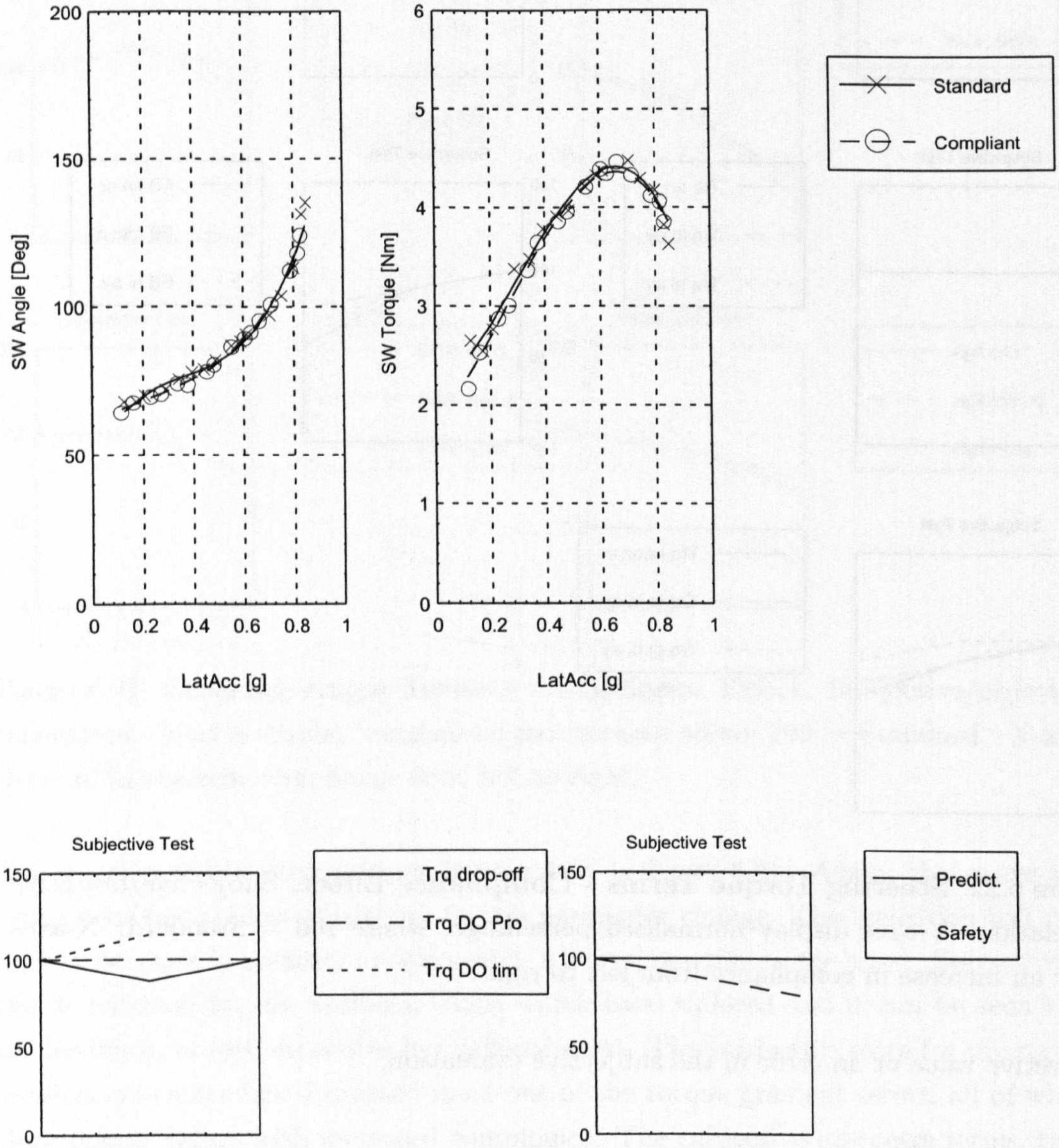

Figure 6.23: **Limit Behaviour - Compliance Effect**. Subjective/objective correlation. Y-axes of second row display normalised percentages where 100 = Standard. X-axes show an increase in compliance from left to right.

Column Friction Variation Results

The friction in the steering column was increased, which altered the vehicle's reaction to the steering torque input. It was hypothesised that this would be the case, while the vehicle reaction to the steering angle would remain unaffected. Upon examination of figure 6.24, it is evident that the measurements show this to be true as there is little consistent deviation from the original values despite the added friction. The theoretical result from the simulation supports the outcome of the measurements. In section 6.3, figures 6.9, 6.10, and 6.11 confirm that there is absolutely no alteration in the vehicle response to steering angle. Although the angular relationship between the steering wheel and the road wheels had not been altered, the subject perceived a change in the steering angles required to operate the vehicle. Furthermore, the subjective agility of the vehicle is perceived to have altered. This can be explained, as the subjective definition of agility is not necessarily the vehicle's reaction to a steering angle input but can also be the vehicle's reaction to a steering input, be it angle or torque.

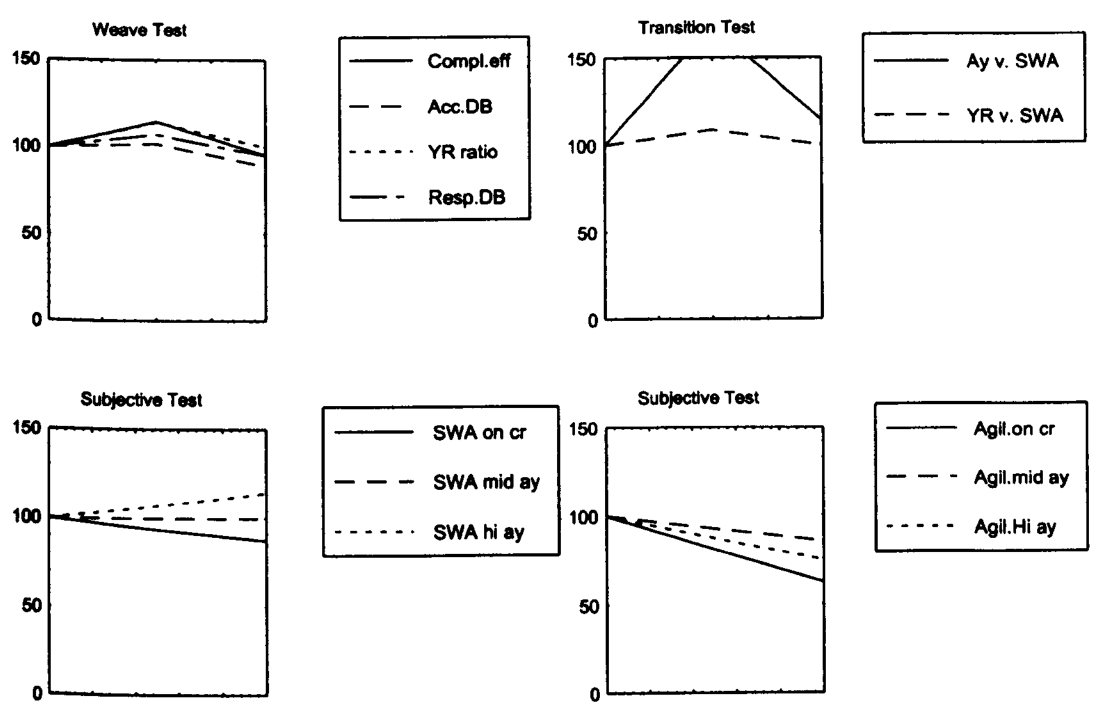

Figure 6.24: **Steering Angle Terms - Column Friction Effect.** Subjective/objective correlation. Y-axes display normalised percentages where 100 = Standard. X-axes show an increase in friction from left to right.

In figure 6.25 the postulated effect of the friction on the driver's evaluation of the car's quality is much more evident. The deadband terms from the weave test and the steering angle/steering torque relationship from the transition test show a distinct decrease (reflecting an increase in double-valuedness). Correspondingly, all subjective scores are detrimentally affected to a large degree with the on-centre terms reaching the lowest values. There is less perceived feedback or feel at higher levels of friction and this effect is less evident as the lateral acceleration increases. This is an effect which shows that the higher friction level is accurately perceived by the driver, since friction has the property that it is more influential at lower excitation levels.

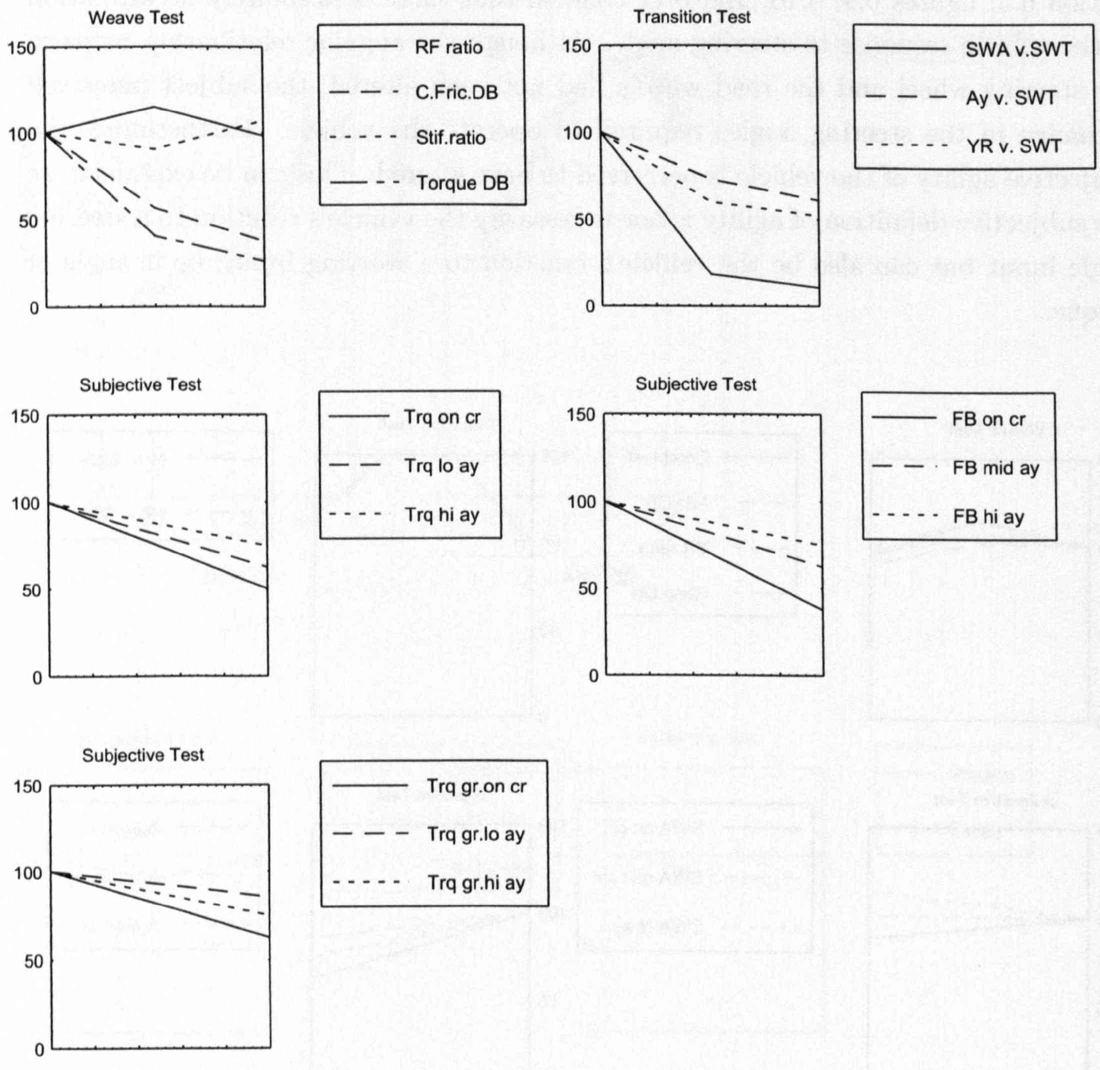

Figure 6.25: **Steering Torque Terms - Column Friction Effect.** Subjective/objective correlation. Y-axes display normalised percentages where 100 = Standard. X-axes show an increase in friction from left to right.

Near the cornering limit, the friction has been seen to completely hide the torque drop-off associated with the tyres reaching their saturation limit. Figure 6.26 contains the result of the stationary circle test in which the loss of correlation between the steering torque and lateral acceleration is evident. The subjective assessment demonstrates that the torque-drop off is not as evident, progressive, or timed as well with extra column friction and consequentially the predictability and safety at the limit have decreased. This supports the hypothesis by which the driver's safety and predictive capabilities are hampered by a lack of information reflecting the grip level at the road wheels.

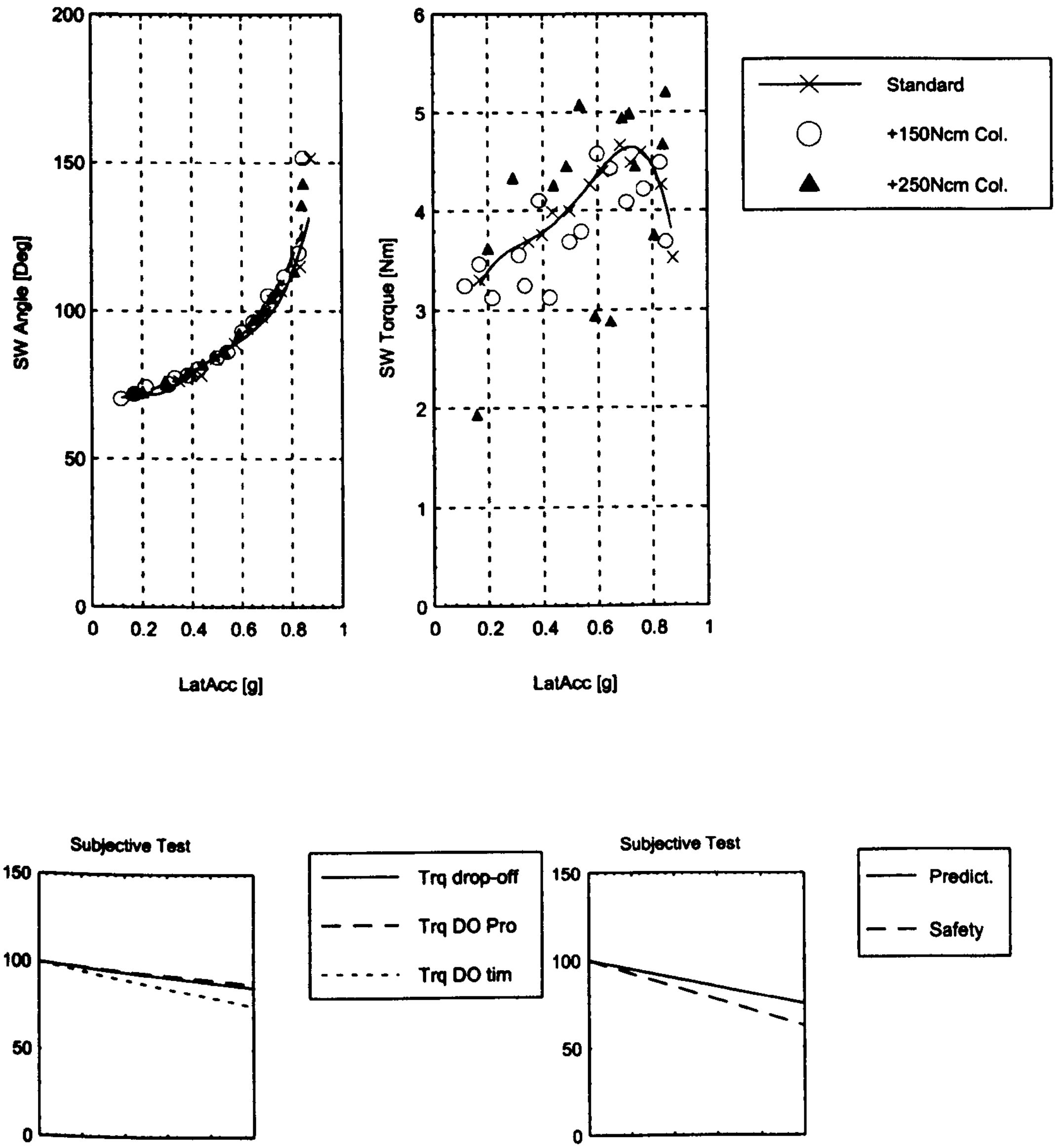

Figure 6.26: **Limit Behaviour - Column Friction Effect.** Subjective/objective correlation. Y-axes of second row display normalised percentages where 100 = Standard. X-axes show an increase in friction from left to right.

Rack Friction Variation Results

In contrast to the case of steering wheel friction, when there is increased friction at the rack, the vehicle's reaction to the steering angle is affected (figure 6.27). The effect, highlighted by the acceleration and response deadbands and the transition test non-linearity, is an increase in the steering angle required to illicit a response from the vehicle. This is reflected by the subjective score for this term and the subjective agility suffers most as a result. Again, the detrimental effect on quality is most apparent in the on-centre area.

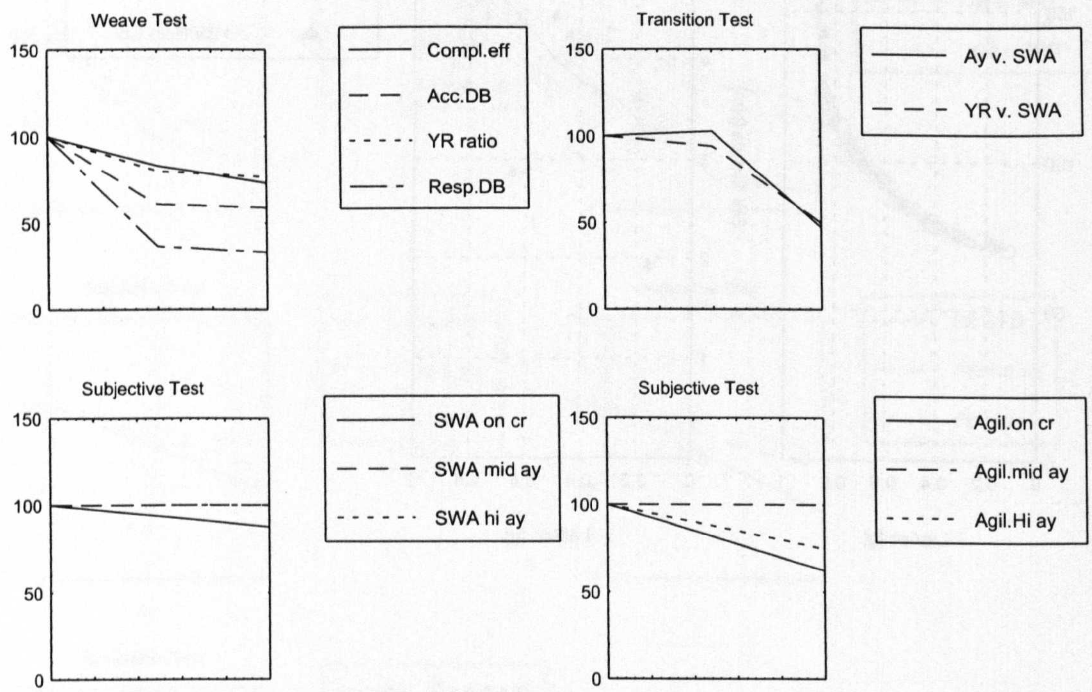

Figure 6.27: **Steering Angle Terms - Rack Friction Effect**. Subjective/objective correlation. Y-axes display normalised percentages where 100 = Standard. X-axes show an increase in friction from left to right.

The torque relationships are, as postulated, altered by the addition of friction on the steering rack. The single-valuedness decreases, reflected by the friction and torque deadbands from the weave test. The linearity measured by the transition test also shows a significant decline (figure 6.28). As at the column, the friction at the rack results in less feedback or feel for the driver. The subjective evaluation of feedback shows how the friction is more detrimental to quality at lower lateral accelerations and, worst of all, on-centre. There is good correlation over all the subjective terms relating to torque with the objective assessment except for feedback at high lateral acceleration. The correlation extends to figure 6.29 where the stationary circle test is insensitive to the rack friction. The subjective assessment of the near limit behaviour similarly shows lack of sensitivity to this parameter variation at high lateral accelerations.

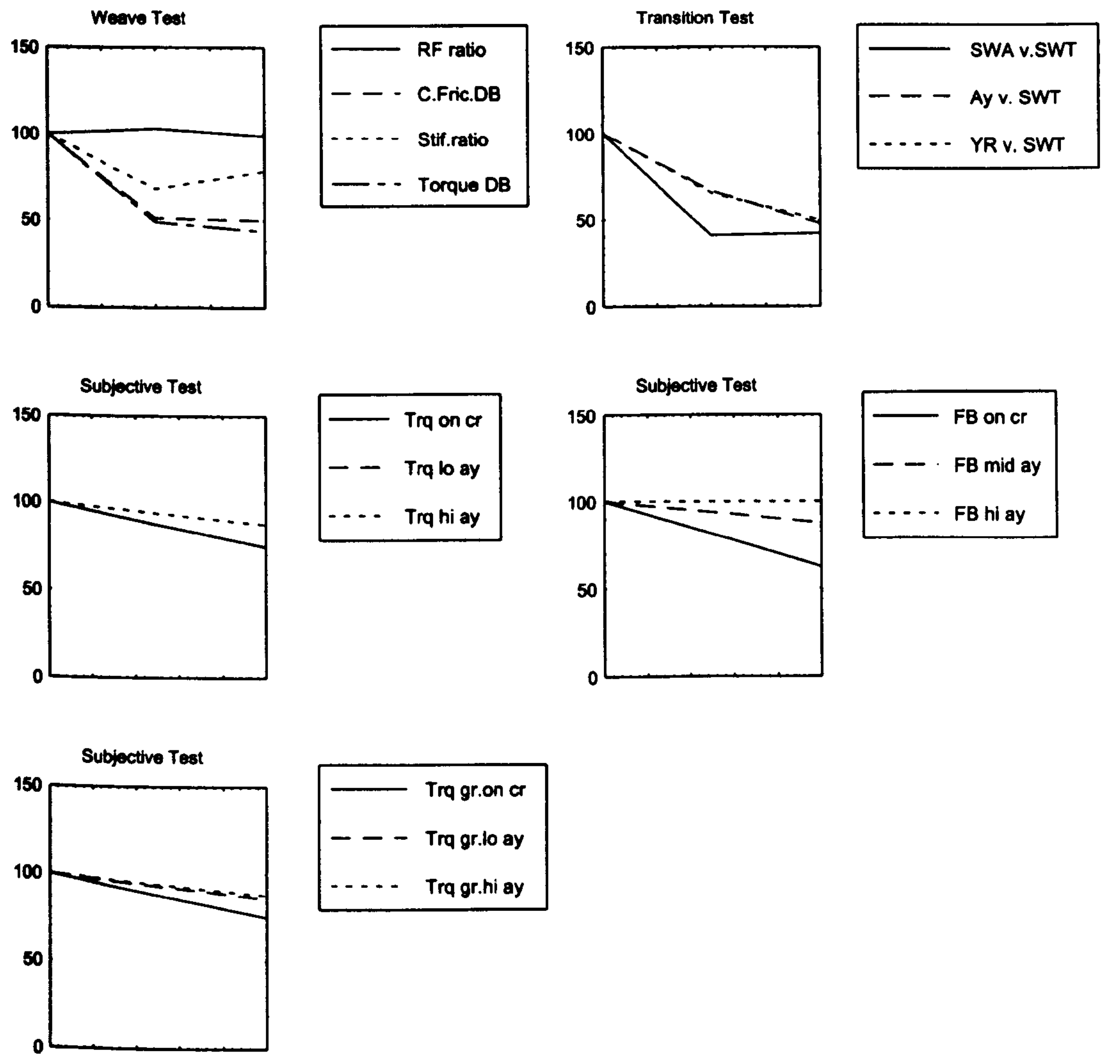

Figure 6.28: **Steering Torque Terms - Rack Friction Effect.** Subjective/objective correlation. Y-axes display normalised percentages where 100 = Standard. X-axes show an increase in friction from left to right.

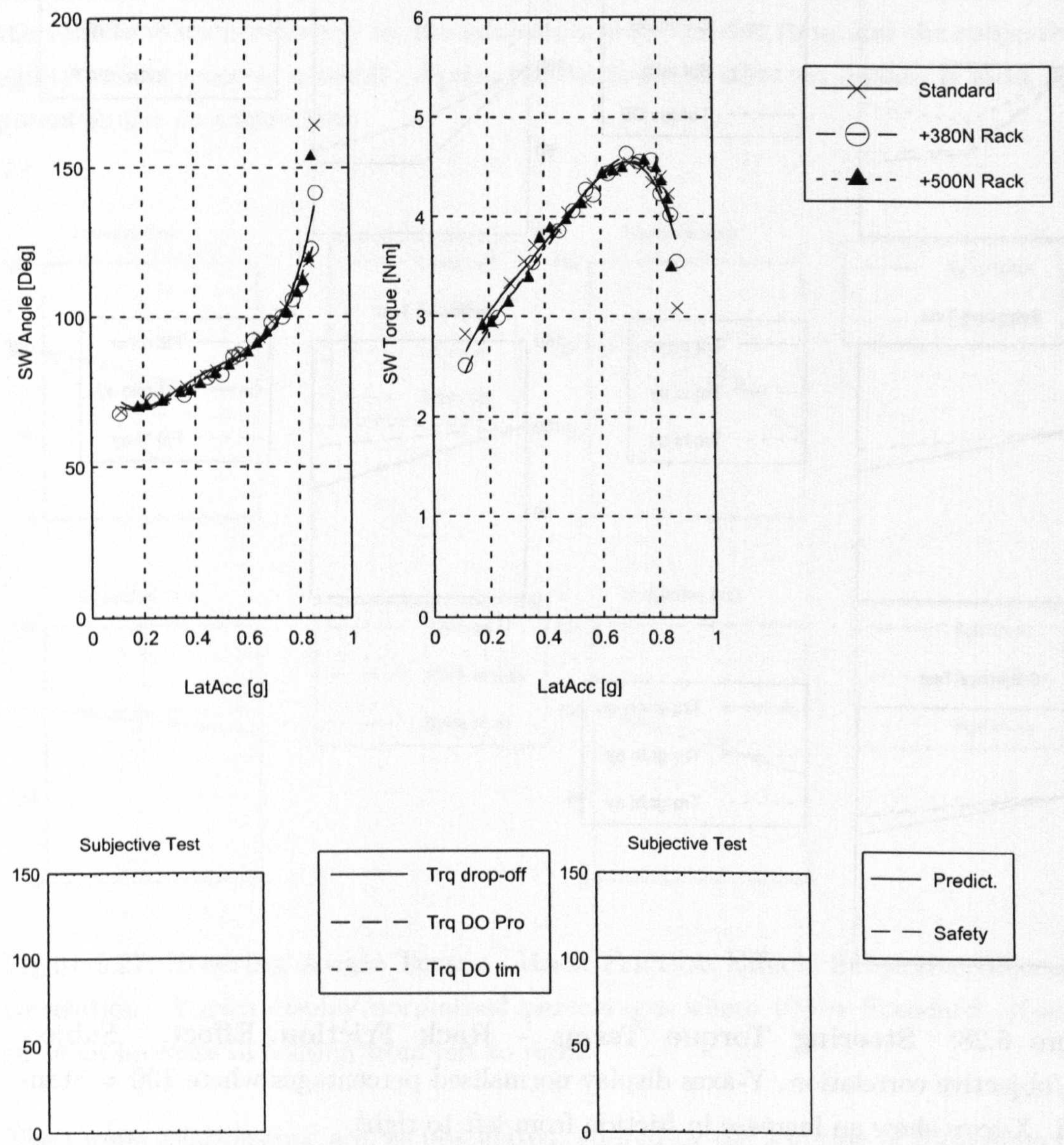

Figure 6.29: **Limit Behaviour - Rack Friction Effect**. Subjective/objective correlation. Y-axes of second row display normalised percentages where 100 = Standard. X-axes show an increase in friction from left to right.

Power Assistance Variation Results

The power assistance provided a just discernible alteration in the measurements of the vehicle lateral reaction to steering angle. It has also been noticed in the simulation, that there is a slight effect (section 6.3, figure 6.16), which is opposite to that of the rack friction. This minimal alteration to the vehicle's properties was also measured by the subjective assessor and is evident in the agility terms in figure 6.30.

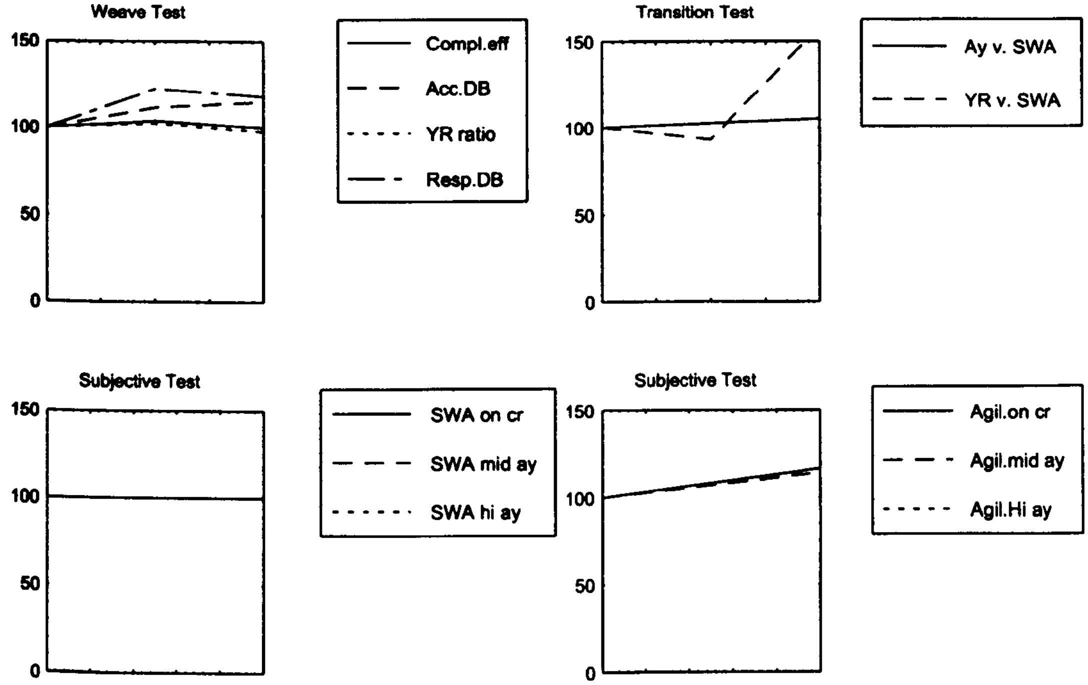

Figure 6.30: **Steering Angle Terms - Power Assistance Effect.** Subjective/objective correlation. Y-axes display normalised percentages where 100 = Standard. X-axes show an increase in assistance from left to right.

The higher levels of hydraulic assistance are more obvious in the vehicle's reaction to a torque input. In figure 6.31, the road feel and stiffness ratios from the weave test and the non-linearity of the transition test highlight, very clearly, the inconsistent torque levels on and off-centre. As the assistance is barely active in the on-centre region, the reduction in torque levels, brought about by extra assistance, occurs when higher lateral accelerations are reached. This is confirmed by the subjective scores for torque and feedback or feel, which depict the lowest scores, reflecting the least quality at highest lateral acceleration.

The circular test produces a result, whereby the torque levels at high lateral accelerations are so low, as to impede the detection of any torque drop-off. Therefore, the tyre information cannot be transmitted to the driver. This is depicted in figure 6.32

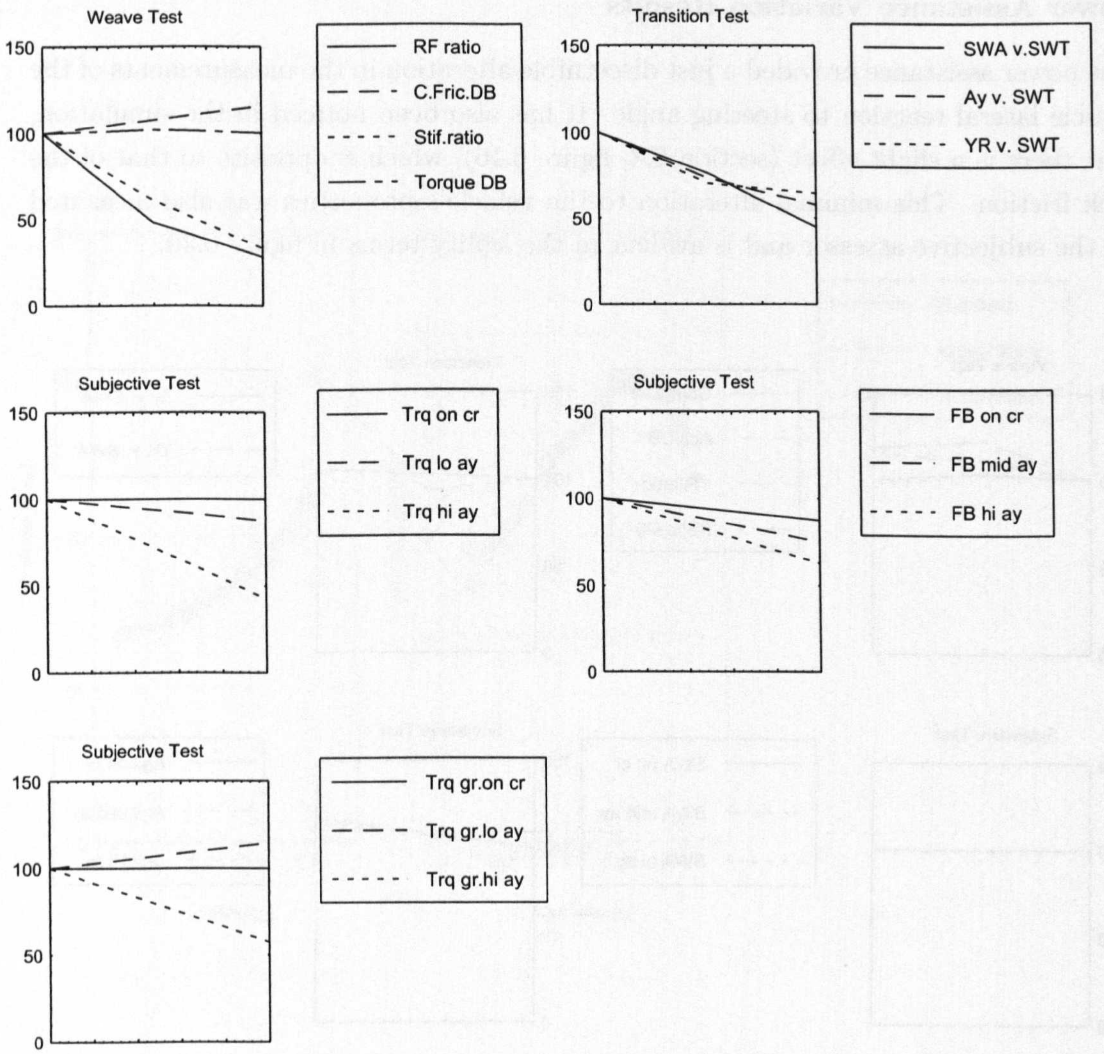

Figure 6.31: **Steering Torque Terms - Power Assistance Effect**. Subjective/objective correlation. Y-axes display normalised percentages where 100 = Standard. X-axes show an increase in assistance from left to right.

where the subjective measures support the hypothesis that this lack of information reduces the steering quality by negatively influencing the safety and predictability of the vehicle.

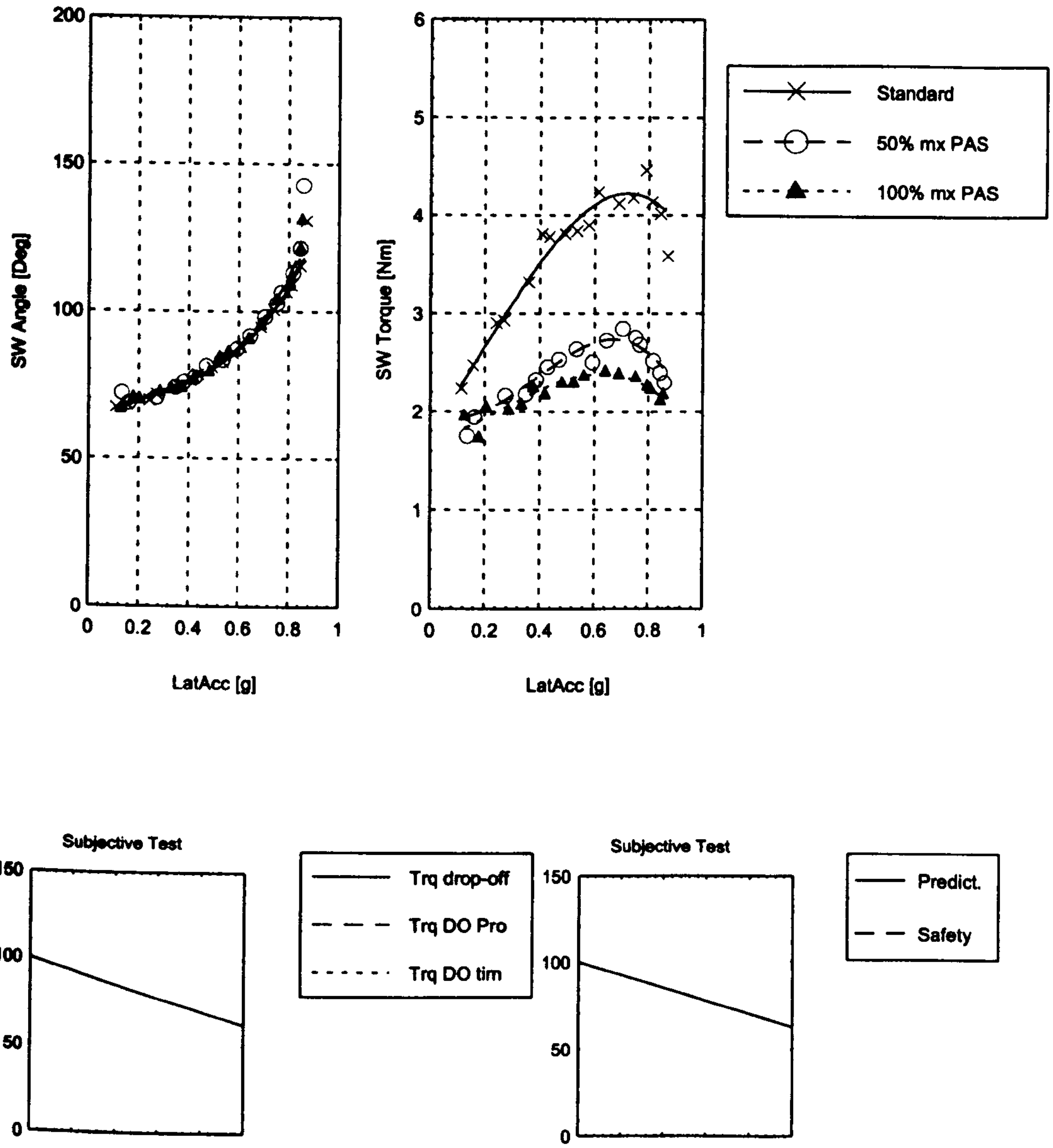

Figure 6.32: **Limit Behaviour - Power Assistance Effect.** Subjective/objective correlation. Y-axes of second row display normalised percentages where 100 = Standard. X-axes show an increase in assistance from left to right.

Free Play Variation Results

Clearance was introduced to the system to alter the vehicle's response to a steering angle input. This has been very clearly identified by the objective assessment. Figure 6.33 contains the weave test results where the deadbands, acceleration and response, reflect the lack of vehicle reaction to the steering angle input. This dead zone region is a non-linearity which is further detected by the transition test where the linearity has severely decreased. As explained in section 4.4.5, the ratios do not reflect the dead zone and thus the change in yaw rate ratio has no correlation with perceived quality. The subjective evaluation shows a large reduction in the on-centre scores with respect to the steering angle terms. This is to be expected, since the clearance is encountered around the steering wheel straight ahead position. The subjective agility at all levels of lateral acceleration has also decreased, showing good correlation with the objective result.

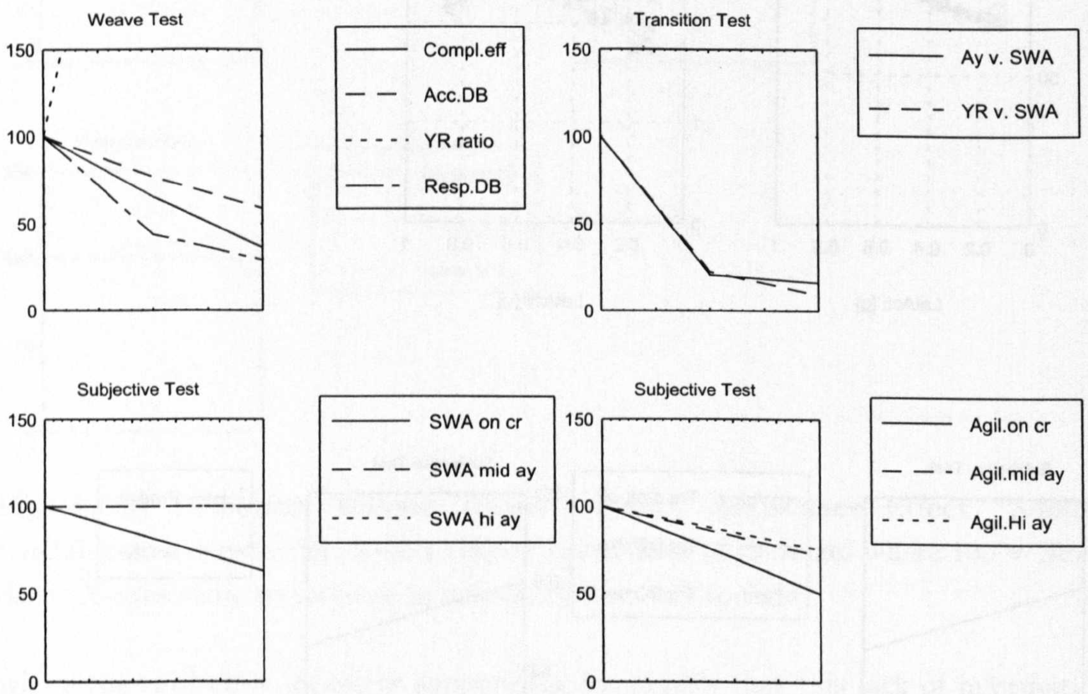

Figure 6.33: **Steering Angle Terms - Free Play Effect**. Subjective/objective correlation. Y-axes display normalised percentages where 100 = Standard. X-axes show an increase in play from left to right.

On examination of figure 6.34, it can be seen that there is also a change in the vehicle's response to a steering torque input. As seen in section 4.4.5, the steering torque/steering angle relationship is altered whereas the vehicle lateral reaction to steering torque remains consistent except in the case of the weave test, where the change of steering direction repeatedly engages the clearance. When comparing the simulation result for the transition test (section 6.3, figure 6.19) with the test result (section 4.4.5, figure 4.48), it can be seen that there is no change in yaw rate and lateral acceleration response to torque in the theoretical result and that the measurements are inconsistent and noisy. This is not the case for the steering torque to steering angle reaction, which shows a definite dead zone in the measurement corresponding to that from the model. Therefore, the objective results from figure 6.34, which provide an accurate representation of the clearance phenomenon, are the torque deadband, the road feel ratio, and the transition test result for steering wheel angle vs. steering wheel torque. The objective qualitative terms representing these three quantities have all decreased with increasing play in the steering column.

The subjective assessment of the vehicle reaction to a torque input (figure 6.34) is most evident in the on-centre region. The subjectively perceived torque is unaffected, correlating with the objective result that the vehicle's lateral reaction to a torque input remained unchanged. The torque gradient scores have decreased, accompanied in the questionnaire by a notation on the discontinuous response. This reflects the steering torque/steering angle relationship, which is objectively described as discontinuous by the road feel ratio and far from ideal by the transition test result. The feedback terms, particularly on-centre, have low scores, which can be attributed to the large dead zone created in the straight ahead position, evident from the torque deadband.

The stationary circle test was not employed for the evaluation of the clearance, as no change was expected in this test. The subjective result shows no alteration in behaviour with added clearance near the limit. The torque drop-off remains completely unaffected as does the predictability, as expected. Only the safety term has decreased and can be explained, as the clearance in the system would affect the positioning of the vehicle and thus contribute to a reduced safety feel.

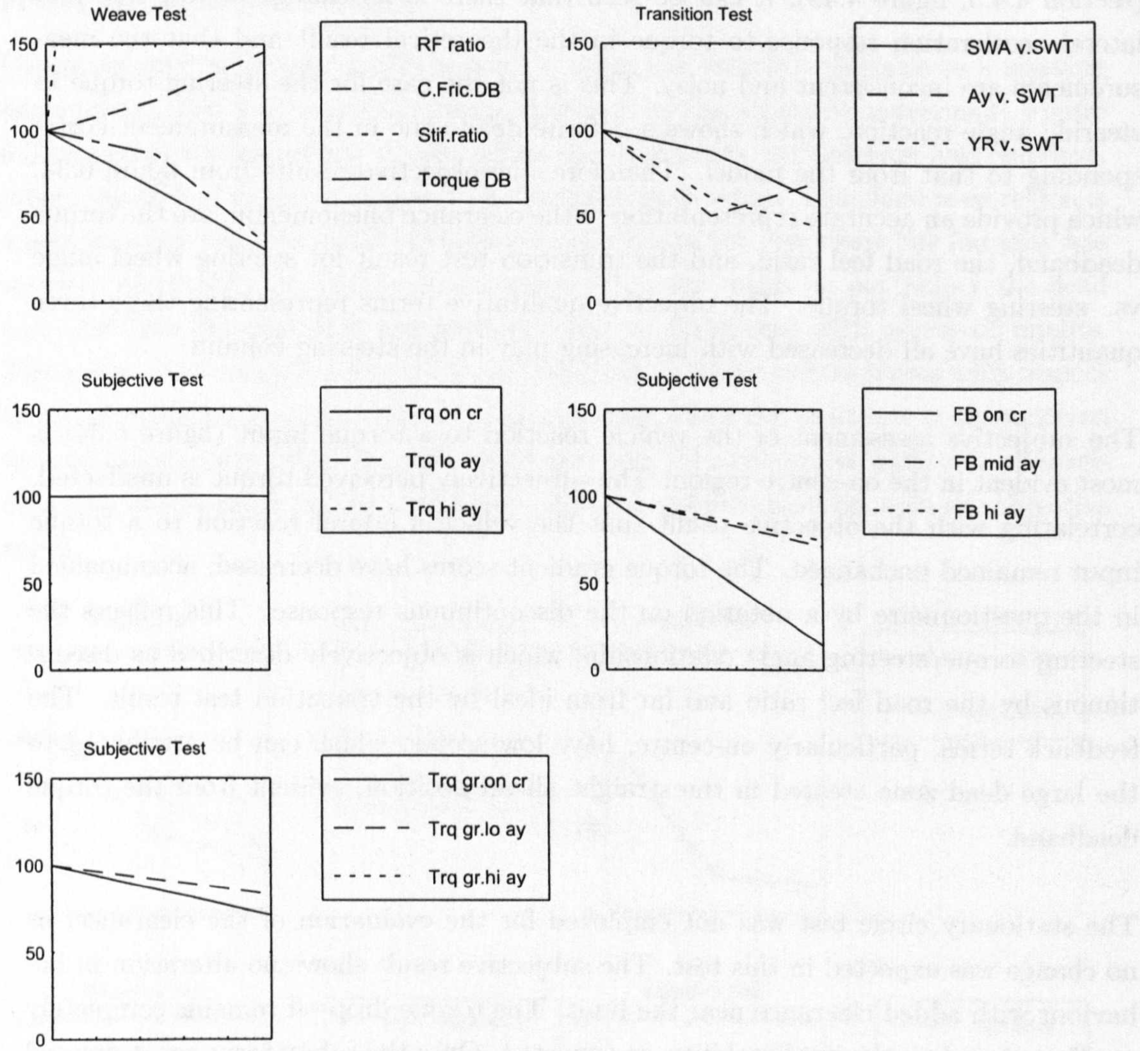

Figure 6.34: **Steering Torque Terms - Free Play Effect**. Subjective/objective correlation. Y-axes display normalised percentages where 100 = Standard. X-axes show an increase in play from left to right.

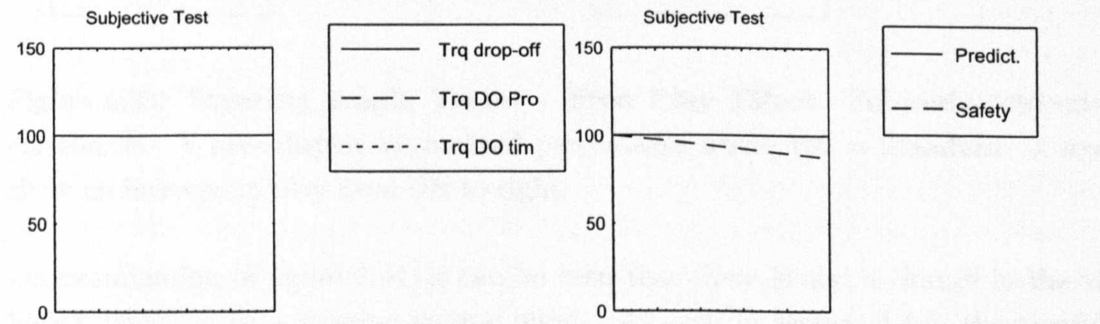

Figure 6.35: **Limit Behaviour - Free Play Effect**. Subjective Evaluation. Y-axes display normalised percentages where 100 = Standard. X-axes show an increase in assistance from left to right.

Chapter 7

Conclusion

7.1 Conclusions

The objective was stated in chapter 1 as the provision of a method for the testing and simulation of steering feel and quality. It has been argued that, through the analysis of the input/output relationships of the vehicle system, it is possible to ascertain the quality of the steering system and thus describe what drivers term steering feel. It was postulated that these relationships should have the following qualities; correlation, consistency, continuity, progressiveness, and single-valuedness. With these qualities present, it is hypothesised that the controller can easily operate the vehicle and be receptive to information output from the system, which is constructive to the predictability and safety of the vehicle operation.

An experiment was designed where a vehicle's properties were altered so as to have postulated detrimental effects on the steering quality. Through a framework of objective testing and simulation, the vehicle system relationships were examined for the qualities outlined by the hypothesis to describe quality and feel. It was found that these analytical methods successfully identified the change in input/output relationships argued to describe quality. The same experiment was conducted with an expert subjective evaluator to assess the effects the altered vehicle properties have on what the driver perceives as steering quality and feel. The correlation achieved between what was hypothesised to affect quality and what is termed quality by the driver was high and consistent. This correlation, dealt with in detail in section 6.4, is summarised in table 7.1.

Table 7.1 shows how the objective measures postulated to describe quality correlate with the subjective assessment of what is described as steering quality and feel. The terms 'Yes' and 'No' refer to whether there was an observed detrimental effect on the quality. 'Slight' represents a small but noticeable effect and '**Yes**' in bold denotes a considerable observed effect. It is evident that in all cases the measurements agree

Variation		Objective	Simulation	Subjective
Elasticity	Reaction to angle	Yes	Yes	Yes
	Reaction to torque	Yes	Yes	Yes
	Torque at limit	No	No	Slight
Column Friction	Reaction to angle	No	No	Yes
	Reaction to torque	**Yes**	**Yes**	**Yes**
	Torque at limit	**Yes**	**Yes**	**Yes**
Rack Friction	Reaction to angle	Yes	Yes	Yes
	Reaction to torque	Yes	Yes	Yes
	Torque at limit	No	No	No
Power Assistance	Reaction to angle	Slight	Slight	Slight
	Reaction to torque	**Yes**	**Yes**	**Yes**
	Torque at limit	**Yes**	**Yes**	**Yes**
Play	Reaction to angle	**Yes**	**Yes**	**Yes**
	Reaction to torque	**Yes**	**Yes**	**Yes**

Table 7.1: Summary of subjective/objective correlation and simulation validation.

with the theoretical model. The objective analysis methods agree with the subjective assessment in all cases bar two. In the first instance, the compliance variation, a single subjective term, inconsistent with other similar subjective terms, does not correlate. In the second instance, the column friction angle reaction, the subjective assessment has apparently included the vehicle's reaction to both angle and torque in the term agility, which is adversely affected by the friction and thus this term correlates with the measured vehicle response to a torque input, as opposed to an angle input.

Aside from these two inconsistencies, the overall correlation is very high. Table 7.2 compares the global subjective evaluation with the outcome of the objective results. The global score is the total score on the 1-10 evaluation index for the subjective assessment of the vehicle's steering. This table shows that what was hypothesised to have a detrimental effect on steering feel and quality can be measured and corresponds to what the driver describes as a steering system of low quality.

It has therefore been shown that what the driver perceived as steering feel and quality, corresponds to certain features of the vehicle's reaction to steering inputs, angle and torque, at low and high levels of lateral acceleration. These features can be measured and drawn from a theoretical model of the vehicle system. Thus, a framework has been provided, where what was described as steering feel and quality by the driver, can be objectively quantified.

Variation	Objective test and simulation	Global score
Column Elasticity Rigid → 0.69 Nm/°	Responses to angle and torque inputs adversely affected	-2.5 Points
Column Friction 0.1 → 2.5 Nm	Responses to torque inputs and limit torque properties severely adversely affected	-3 Points
Rack Friction 120 → 500 N	Responses to angle and torque inputs and limit torque properties adversely affected	-2 Points
Power Assistance 0 mA → 859 mA	Responses to torque inputs and limit torque properties severely adversely affected	-2 Points
Play 0 → 10°	Responses to angle and torque inputs severely adversely affected	-5 Points

Table 7.2: Global subjective/objective correlation.

7.2 Application to Vehicle Design and Engineering

The procedure for the objective assessment of the steering system is given in figure 7.1. This methodology has been used to assess the quality of the vehicle configurations tested. It is noted, however, that the configurations involved extreme differences and thus the effects of these could be clearly quantified. Such extreme differences are rarely encountered in practice. In fact, steering feel is a term typically involved in the distinction of vehicles, or configurations, where the differences are slight and are conventionally described subjectively. While the experiment aimed to introduce variations to affect either the reaction to steering wheel angle or the reaction to steering wheel torque, it was observed that there were secondary effects where this was not the case. For example; the increase in rack friction and power assistance resulted in, not only a marked alteration in the response to the torque input, but a change in the vehicle's reaction to the steering wheel angle. This was evident to a degree from the objective measurements and more so in the vehicle simulation. Therefore, the smaller variances were also quantified by this method and it is suggested that slight differences in quality describing steering feel can be similarly evaluated.

In formulating the procedure in figure 7.1, good feel and control properties were postulated with reference to the input/output relationships of the steering system. These properties were:

- Maximum sustained correlation.
- Maximum single-valuedness and lack of dead zones and hysteresis.
- Continuity and progressiveness in any change of behaviour between operating points.

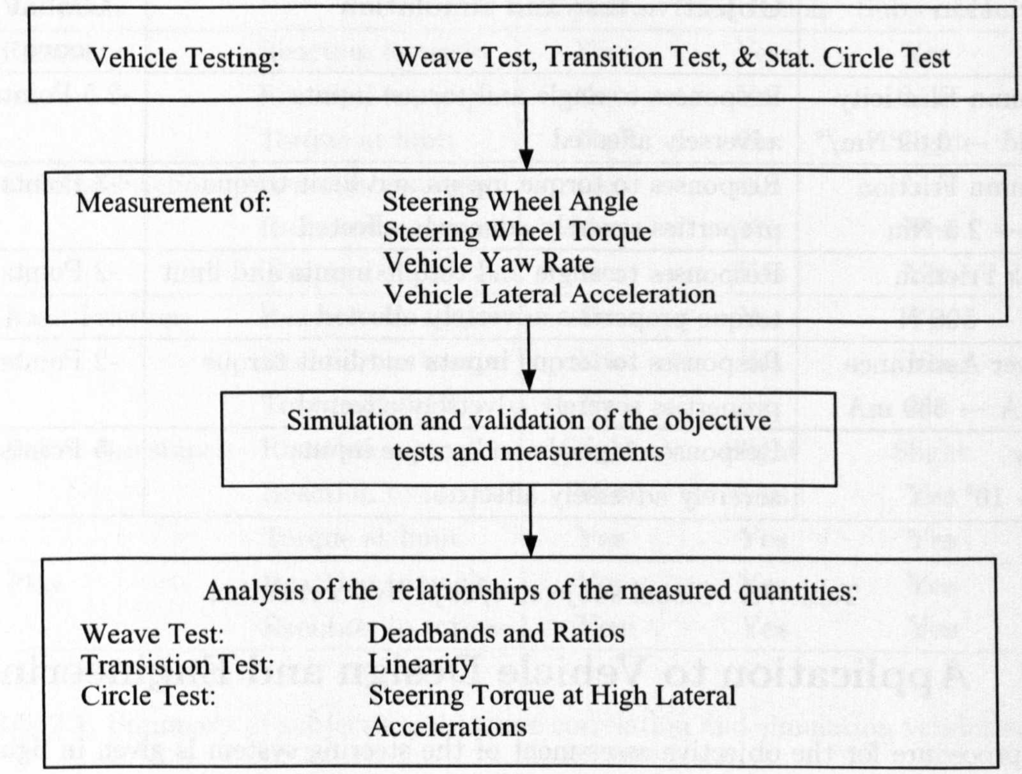

Figure 7.1: Objective analysis procedure and methodology for the assessment of the steering system.

These properties were described by objective quantities measured during the testing procedure and were found to correlate with the driver's perception of high quality. Therefore, the conclusions in table 7.3 can be drawn. This table can be used as an indicator of the properties to include in an effort to create a steering design, which results in customer satisfaction. Upon examination of the findings of the control experiment, some conclusions can be drawn as to how the variable parameters contribute to these properties. Table 7.4 summarises the findings and details the adverse effects of the parameters. It follows from the findings, that the elasticity, friction, play and power assistance should be kept to a minimum, as far as possible, while maintaining functionality. Furthermore, the disadvantages in the combination of rack friction and compliance are highlighted, while the power assistance can be seen to reduce the effect of rack friction and very slightly improve the response to steering angle input.

As technology and production methods improve, the acceptable standard of production cars continually increases. The customer accepts less compromises and therefore the quality of vehicles reaches an extremely high level. Identifying a car's faults as a means of evaluation is becoming increasingly difficult, since there are less imperfec-

Weave Test	
Quality *increases* as the following objective quantities *decrease*:	
Steering Compliance Effect	Acceleration Deadband
Yaw Rate Response Gain Ratio	Response Deadband
Road Feel Ratio	Coulomb Friction Deadband
Steering Stiffness Ratio	Torque Deadband
Transition Test	
Quality *increases* as the linearity of the following relationships *increases*:	
Steering wheel angle vs. Lateral acceleration	
Steering wheel angle vs. Yaw rate	
Steering wheel torque vs. Steering wheel angle	
Steering wheel torque vs. Lateral acceleration	
Steering wheel torque vs. Yaw rate	
Stationary Circle Test	
Steering wheel torque vs. Lateral acceleration relationship:	
A progressive and detectable torque drop-off near the limit is a requirement for steering quality	

Table 7.3: Objective qualification of the steering system.

tions. Often, the factor differentiating two vehicles is difficult to express in physical terms and this is the case with steering quality and feel. The methods outlined in this thesis are a step towards the quantification of these differences in high-end quality which, up until now, have been identifiable only by subjective opinions. The testing methods also allow a vehicle to be assessed objectively without the need for highly experienced subjective evaluators and provides a scientific method for the comparison of different vehicles or vehicle configurations.

Simulation has been used in this thesis to provide a theoretical result as a means of validation of the measurements. Good correlation has been shown between the simulation results and the vehicle measurements in section 5.3. This could present an opportunity in the future to make rational steering quality design decisions in the pre-prototype stage of vehicle design.

Electronics and mechatronics are becoming increasingly commonplace in the automotive industry and this area looks set to continue growing. Electronic steering [Backhaus 1998] removes the need for a hydraulic steering pump which is typically continually driven by, and thus draws power from, the engine. This reduces the fuel consumption of the vehicle which is a vital factor in conforming with emissions standards. Electronic control systems are also used in an effort to improve safety as with

Variable Parameter	Finding
Elasticity	An increase in compliance has a negative effect on the responses of the vehicle to steering wheel angle. This worsens when combined with increased system friction to further increase the steering angle required to manœuvre the vehicle.
Column Friction	This parameter results in a dead zone in the vehicle response to torque input. As this torque increase must be overcome before the torsion bar is twisted, the hydraulics cannot compensate with power assistance. It thus severely hampers feedback and system identification by the driver.
Rack Friction	Rack friction also creates a dead zone in the response to torque inputs. However, the power assistance compensates for the increase in torque and the effect is, in part, counteracted. In combination with system compliance, the response to angle inputs also deteriorates significantly.
Power Assistance	The difference in behaviour on and off-centre introduced, results in inconsistent system behaviour. The reduced torque levels off-centre also remove the driver's ability to detect information contained in the torque/lateral acceleration relationship. In contrast with the negative consequences of combining rack friction with compliance, the power assistance reduces the compliance effect and can result in a slightly better response to steering angle input.
Play	The clearance yields a very prominent dead zone in the vehicle's reaction to a steering angle input. The inconsistent behaviour lacks progressiveness, as there is an immediate behavioural change as the clearance is surpassed and contact is established.

Table 7.4: Findings of the control experiment directly applicable to steering system design.

active front steering [Fleck 2001]. Both these uses of electronics have a high degree of functionality. However, they can have adverse effects on steering feel. It is therefore important that there exists a method of analysis to quantify the effects of new developments, such as these control systems, on the steering quality.

Commonplace in the aircraft industry, 'steer-by-wire' technologies are now being investigated in the automobile sector. This involves the mechanical separation of the steering wheel from the road wheels [Blumenstock 2000b]. In some cases the steering wheel can be replaced by some manner of control stick [Mercedes-Benz Lenkungen GmbH 2001, Blumenstock 2000a]. The relationship between the steering input and the vehicle reaction can be independent of the friction, elasticity, or any other physical property of the steering system. It can be programmed by means of software and therefore any relationship is attainable. The question then remains: What relationship produces good feel and control properties and how can this be measured? This thesis brings us closer to the answer to that question by detailing what constitutes good feel and good control properties and further provides an objective assessment method (figure 7.1 and table 7.3) to allow quantification.

Appendix A

A.1 Test Vehicle Measurement Configuration

Measured Quantity	Sensor Type	Range	Res.	Unit
Vehicle long. speed	Datron Sensor V1	0.25-250	0.1	km/h
Vehicle lateral speed	Datron Sensor V1	± 50	0.1	km/h
Steering wheel angle	BMW Series Sensor	± 1433	0.04375	°
Steering wheel torque	Strain Gauge (DMS)	± 100	ca. 0.1	Nm
Vehicle lat. accel.	Stab. Platform FES33	± 39.228	0.001197	m/s^2
Vehicle long. accel.	Stab. Platform FES33	± 39.228	0.001197	m/s^2
Vehicle yaw rate	Stab. Platform FES33	± 128	0.003906	°/s
Vehicle yaw angle	Stab. Platform FES33	±180	0.00549	°
Vehicle pitch angle	Stab. Platform FES33	±89	0.00549	°
Vehicle roll angle	Stab. Platform FES33	±89	0.00549	°
Steering rack displ.	HBM WA 200-L	±100	ca. 0.5	mm
Track rod force	Strain Gauge (DMS)	± 10000	ca. 10	N
Power assist press.	SA210 Pressure Sensor	0-210	ca. 1	bar

Table A.1: Measurement equipment specification including range and resolution.

Figure A.1: Test Vehicle.

A.2 Inertial Effects

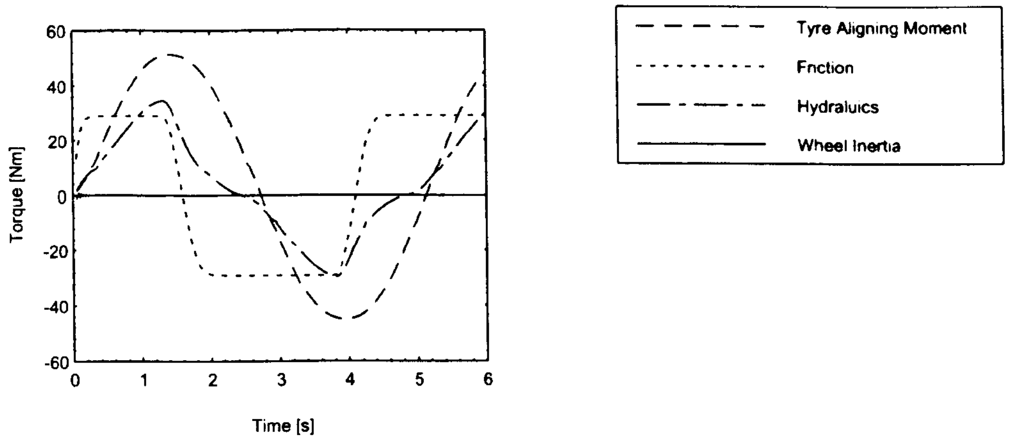

Figure A.2: The inertial effects of the **road wheel** are shown to be small in comparison to the moments on the road wheel. Here the weave test is simulated. The test is the highest in frequency, at 0.2 Hz, of all tests conducted in the experiment.

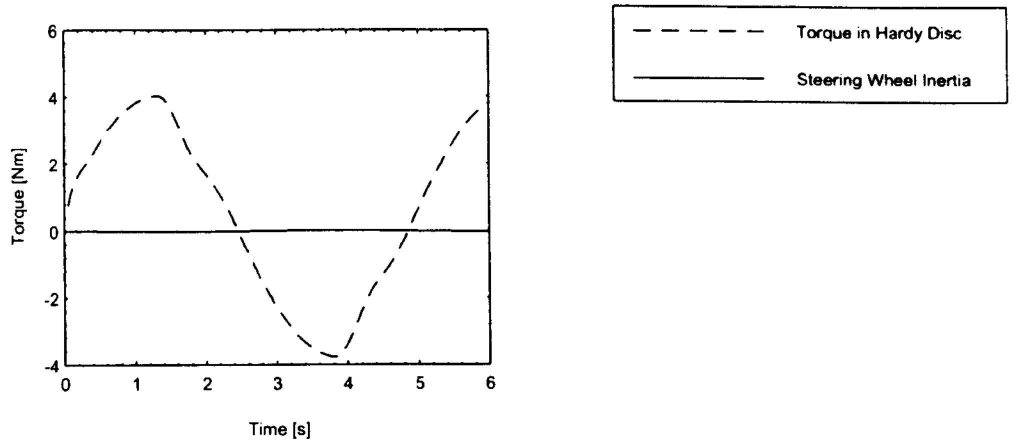

Figure A.3: The inertial effects of the **steering wheel** are shown to be small in comparison to the moment generated on the steering wheel when turning the pinion. Here the weave test is simulated. The test is the highest in frequency, at 0.2 Hz, of all tests conducted in the experiment.

A.3 Steering Control

$$\delta_H = \frac{i\,l}{\rho} + m\,i\frac{C_R\,l_R - C_F\,l_F}{C_F\,C_R\,l}\,\frac{v^2}{\rho} \tag{A.1}$$

C_F and C_R denote the ratio of slip angle to side force, as opposed to cornering stiffness.

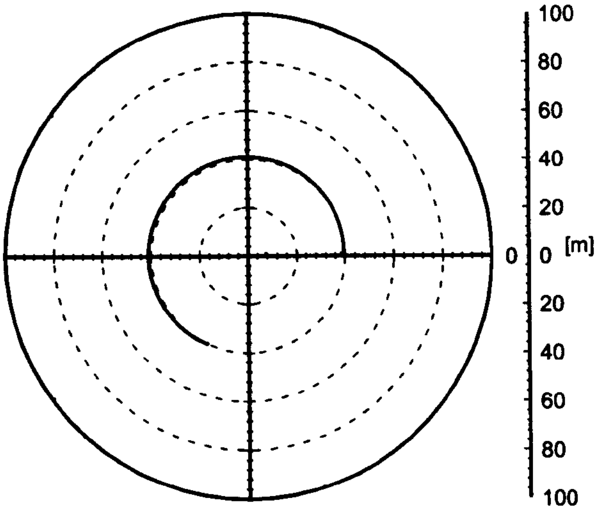

Figure A.4: Simulated Vehicle path for the 40m Circular Test.

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