Das Reifenprofil beeinflußt die Seitenkraftbeiwerte (Seitenkraft/ Radlast) vornehmlich bei den Böden Wiese und Stoppelfeld. Die abstützbaren Seitenkräfte sind bei einem Schräglaufwinkel von 30° bei den profilierten Reifen gegenüber dem glatten Reifen um 25 bis 70 % höher. Das typische Lenkreifenprofil mit zwei tiefen Rundum-Rillen bei 3 Rundum-Hochstollen erzeugt bei geringen Schräglaufwinkeln zwar kleinere Seitenkräfte, kann aber bei großen Schräglaufwinkeln die größten Seitenkräfte abstützen. Das Treibradprofil ist in fast allen Fällen in Laufrichtung richtig montiert vorteilhafter als rückwärtslaufend montiert. Der Terra-Reifen schneidet bei pflanzenbedeckter Oberfläche gut ab, bringt aber keine nennenswerten Vorteile auf glatter Bodenoberfläche.

Die Rollwiderstandsbeiwerte (Längskraft/Radlast) sind in fast allen Fällen für profilierte Reifen im Mittel um 15 bis 40 % höher als bei dem unprofilierten Reifen. Sie betragen bei 15° Schräglaufwinkel für Kies 0,15–0,22, für Wiese und Stoppelfeld 0,18–0,27 und für gegrubberten Acker 0,25–0,32.

Die Ergebnisse dieser Seitenkraft- und Rollwiderstandsmessungen an Implement-Reifen mit unterschiedlichen Profilen sind nützlich für die Berechnung:

1. der notwendigen Vorderachslast für das sichere Lenkverhalten von Schleppern (schräger Zug);
2. der Lastannahmen von Rädern, Achsen und Reifen;
3. der notwendigen Leistung zur Überwindung des Rollwiderstandes der Schleppervorderachse bzw. der Hinterachse beim Mähdrescher;
4. der Lenkfähigkeit und Stabilität von Schleppern und Anhängern am Hang;
5. des allgemeinen Fahrverhaltens des Schleppers (Computer-Simulation).

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Measurement of the response of tractor steering systems

Von Richard Mildmay Stayner, Donald James Bottoms and Ian Watkins, Silsoe

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The response of a tractor's hydrostatic steering system was measured under a range of conditions. The steering ratio was found to vary between 9,5 : 1 and 14,5 : 1 and the time lag in the system was found to vary between 0,04 s and 0,14 s. It is suggested that these factors may have an adverse effect on drivers' steering performance. It is proposed that comparative tests of steering system response need to include dynamic measurements with the tractor in motion.

Das Übertragungsverhalten eines hydrostatischen Lenksystems wurde bei einer Reihe verschiedener Bedingungen gemessen. Dabei wurde festgestellt, daß die Übersetzung der Lenkung zwischen 9,5:1 und 14,5:1 schwankt und die Totzeit im System zwischen 0,04 s und 0,14 s. Es ist zu vermuten, daß diese Faktoren das Lenkvermögen des Fahrers ungünstig beeinflussen. Vorgeschlagen wird, bei vergleichenden Untersuchungen des Lenkungs-Übertragungsverhaltens dynamische Messungen mit fahrendem Schlepper mit einzubeziehen.

**) R.M. Stayner, Head of Ergonomics Department at NIAE, D.J. Bottoms, Research Engineer (workplace design and tractor steering), Ergonomics Department NIAE and I. Watkins, Ergonomics student, University of Loughborough.*

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1. Introduction

The study is a small part of a larger project. The purpose of the main project is to find out what factors affect the accuracy with which drivers can make their tractors, or the implements attached to their tractors, follow a set course. The factors which we need to consider, **Table 1**, include some which may be affected by machine design, such as visibility of the point where the implement meets the crop or the ground, response of the tractor to steering movements or response of the implement to tractor movements. They include too some factors which are beyond the designer's control, notably the roughness of the ground surface, the softness of the soil and the adhesion between the tyres and the soil. If we can improve the accuracy with which drivers can steer their tractors, then we can expect increased work rates in the field and greater safety on the road.

We have developed, at the NIAE, a method of measuring the errors which occur when a driver tries to guide an implement along a marked course [1]. It is our plan to use this method to investigate the factors mentioned above. However, if we consider just the one factor of the response of the tractor steering system, it is clear that we need a laboratory test of this response which we can relate to the drivers' performance in the field trials, and which the development engineer can use to compare the changes he may want to make to the steering system. It is not clear which is the most appropriate measurement to make, so we started with the work reported here which is simply a set of laboratory measurements of the response of one particular type of steering system, namely a full power, hydrostatic system fitted to a medium sized, two wheel drive tractor.

Design Factors
◎ Visibility: driver position, implement position
○ Steering system response
○ Tractor response
○ Implement response
Uncontrolled Factors
■ Ground surface: roughness, softness, adhesion

Table 1. Tractor steering accuracy.
Schlepper-Lenkgenauigkeit.

2. Measurements

2.1 Equipment

We measured the rotation of the steering wheel using a potentiometer driven by a toothed belt, and the rotation of both front wheels about their king-pins. For this we used potentiometers attached directly. The electrical signals from the two front wheels were added to give a single, averaged value, **Fig. 1**. Depending on the test conditions, the two electrical signals (steering wheel and front wheels) could be measured directly on a voltmeter or from a chart recorder, fed to an analyser (Fourier Analyser, Hewlett Packard 5420A), or recorded on magnetic tape for analysis at a later time.

2.2 Test procedures

We used various test conditions, **Table 2**:

1. The static response with the tractor stationary: For this the steering wheel was moved by small increments from full left lock to full right lock and back again. The positions of steering wheel and front wheels could be measured directly in this test to give us a simple "steering ratio".
2. Transient response, tractor moving: For this the steering wheel was moved quickly through a fixed angle of 30° either to left or to right as the tractor was driven along a level concrete test track. The measurements from the potentiometers were recorded and later plotted out to give values of steering ratio and of any time lag in the system.
3. Response to random input, tractor stationary: This test was used to measure the frequency response of the system. In order to run the test we had to find a way of creating the random input. We chose to use a human operator, even though this introduces a problem. If a man is asked to move the steering wheel in a random fashion, his natural movements tend to a narrow band of frequency between 0,3 and 0,5 Hz. Our solution was to provide a compensatory type of tracking task, **Fig. 2**. In this the operator had to use an electrical signal from the steering wheel to compensate or cancel a demand signal from a random source. He could watch the error on an oscilloscope and he had to try to keep the spot in the middle of the screen. In this way his movement of the wheel could be forced to include frequencies from zero up to the limit of his response. We found that limiting the demand signal to a 0,7 Hz bandwidth led to a good response from the operator. With this input we measured the transfer function, or frequency response function, between the steering wheel signal and the front wheel signal. We measured also the coherence function between the two signals.
4. Response to random input, tractor moving: The operator who had been trained to use the compensatory tracking task described above was able to produce quite broad-band steering movements even without the aid of the tracking task. This gave us the possibility of measuring frequency response while the tractor was moving.
5. Frequency response, driving a straight course: Finally we found that a driver needed to make continuous steering corrections just in order to maintain a straight course which gave sufficient signal to measure the frequency response of the system. We used this form of measurement for travel over both smooth and rough surfaces and at medium and high speeds.

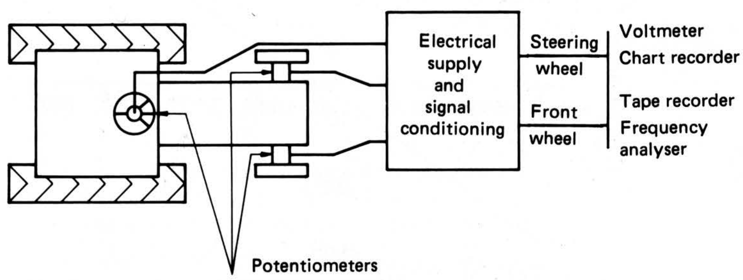

Fig. 1. Measuring system for steering response.
Meßsystem für das Übertragungsverhalten des Lenksystems.

Tractor Stationary
○ Static or steady static input
○ Random input
Tractor in motion
○ Transient or ramp input
○ Random input
Real input to maintain straight course – smooth surface – rough surface

Table 2. Steering system response – test conditions.
Versuchsbedingungen für das Übertragungsverhalten der Lenkung.

For this range of test conditions we obtained results which were not altogether consistent.

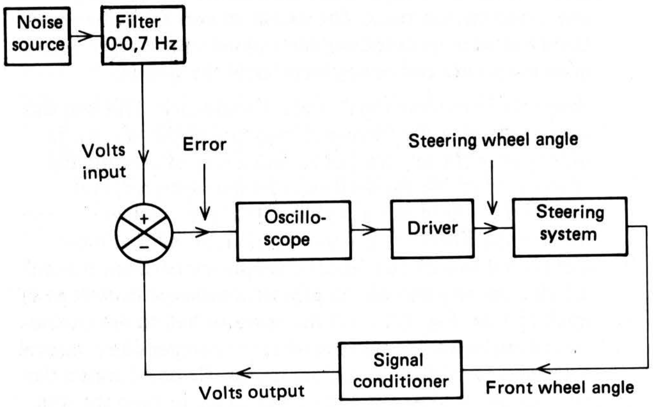

Fig. 2. Compensatory tracking task.
Kompensatorische Tracking-Aufgabe.

3. Results

3.1 Static steering ratio

First, for the static test we have the front wheel angle plotted against steering wheel angle, **Fig. 3**. Slight deviations from a straight line are caused by the difference in angles of the two front wheels as they approach the maximum steering angle. Under these conditions, the ratio between front wheels and steering wheel, the Steering Ratio, was 13,6 : 1 and it was the same whether the wheels were raised in the air or on the ground and subject to tyre scrubbing forces.

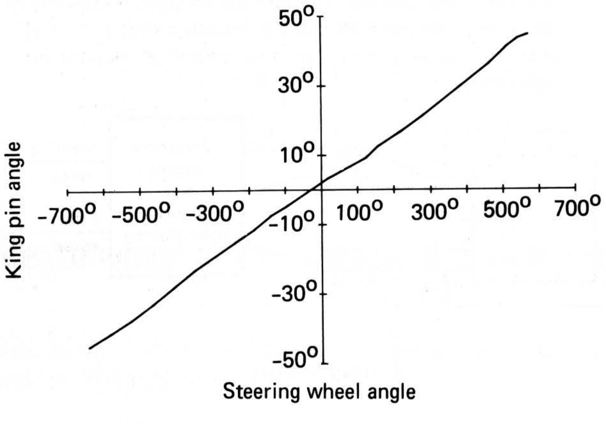

Fig. 3. Static steering ratio.
Statische Lenkübersetzung.

3.2 Response to simple transient demand

Next, for the ramp input with the tractor moving, we recorded responses of which **Fig. 4** is typical. The upper trace shows steering wheel angle, the lower one front wheel angle, both as they vary with time. From the steady state angles at the end of the manoeuvre we measured the steering ratio. We could also measure a delay of about 100 ms between movement of the steering wheel and movement of the front wheels. The steering ratio found in this test was not constant but varied between 12,9 : 1 and 14,8 : 1, **Table 3**. For higher tractor forward speeds the ratio increased. In other words the steering wheel had to be moved further to achieve the same movement of the front wheels. Also the ratio was higher for right hand turns than for left hand turns.

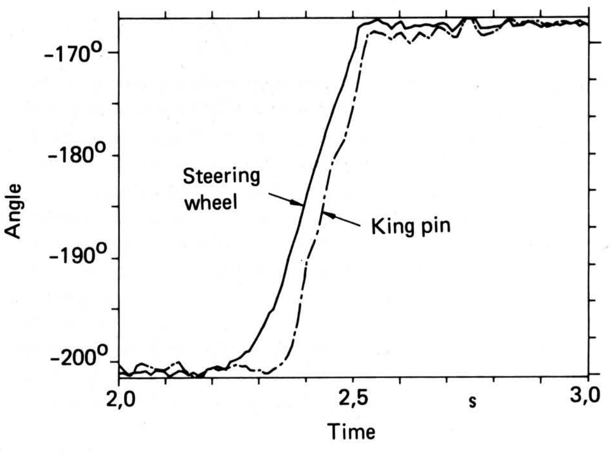

Fig. 4. Transient response of tractor steering system; 4,8 km/h.
Übergangsverhalten des Schlepper-Lenksystems; 4,8 km/h.

Tractor speed km/h	steering ratio	
	Anti-clockwise	Clockwise
4,8	12,9 : 1	13,2 : 1
9,6	13,6 : 1	14,0 : 1
14,4	14,4 : 1	14,8 : 1

Table 3. Steering ratio – transient test.
Lenkübersetzung – Bestimmung des Übergangsverhaltens.

3.3 Frequency response to random demands

For the frequency response measurements, we were able to generate a random input, as described above, with a bandwidth of about 0,7 Hz, **Fig. 5**. The power spectral density of this input signal is not as flat as we would want for an ideal, standardised test, but there is enough signal power to provide good coherence between input and output at frequencies up to 1 Hz, and sometimes higher. The magnitude of the frequency response function, **Fig. 6**, varies with frequency. For the stationary tractor, which this figure shows, the steering ratio varies between about 8,8 : 1 at about 0,1 Hz and about 20 : 1 at 1,5 Hz.

At the lower frequencies the phase lag is proportional to frequency, and is equivalent to a constant time delay of about 0,14 s in the case shown.

At this point it is worth remembering that the steering system which we were studying was a hydrostatic type. In this system motion is transferred to the front wheels only when the valve controlled by the steering wheel is open. High frequency movements of small amplitude are less likely to open the valve than low frequency movements of larger amplitude. This suggests that there is an increase in lost motion at higher frequencies, and that may be one of the most important reasons why the apparent steering ratio increases with frequency. To measure frequency response function, we must assume that the system is linear in its response. It is clearly not linear, and so we must interpret these measurements with great care.

The frequency response measurements which we have made cover the test conditions shown in **Table 4**, together with the tractor stationary. We used the speed of 6,5 km/h for both rough and smooth roadways, and for comparison of our artificial, random steering movements with the movements needed to keep a straight course. The last test was at the higher speed of 24 km/h over the rougher farm roadway.

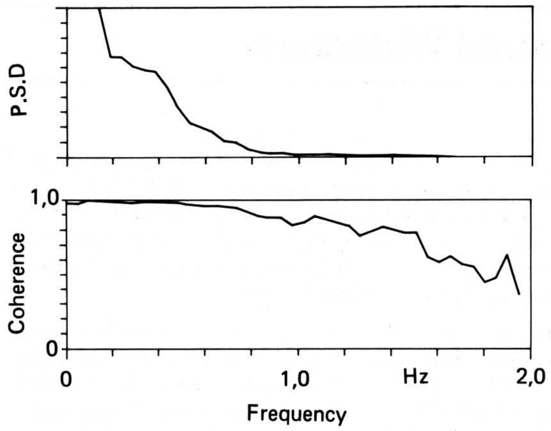

Fig. 5. "Random" input to steering wheel generated by driver using compensatory tracking task.
Stochastisches Eingangssignal am Lenkrad, erzeugt durch den Fahrer bei Durchführung der kompensatorischen Tracking-Aufgabe.

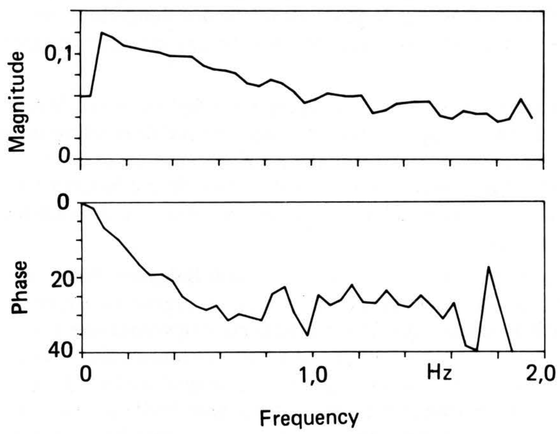

Fig. 6. Transfer function "random" input.
Übertragungsfunktion für ein stochastisches Eingangssignal.

Trial No.	Surface	Nominal speed km/h	Driver's steering wheel input
1	Tarmac road	6,5	Pseudo random signal
2	Tarmac road	6,5	Normal driving, attempting to keep straight course
3	Rough farm track	6,5	Normal driving, attempting to keep straight course
4	Rough farm track	24,0	Normal driving, attempting to keep straight course

Table 4. Conditions for measurement of dynamic response – frequency domain.
Bedingungen für die Messung des dynamischen Übertragungsverhaltens – Frequenzbereich.

The results, **Table 5**, show a range of steering ratios measured at frequencies of 0,1 Hz and 0,6 Hz which are between 9,3 : 1 and 12,8 : 1 for the moving tractor. The ratio is consistently higher at the higher frequency, although sometimes the difference is very small. Values for frequencies higher than 0,6 Hz are unlikely to have very much meaning. The time delay in the system varies between 0,04 s and 0,14 s. The size of this delay, and the amount by which it can vary, are likely to make the driver's steering task more difficult than with a direct mechanical steering system.

Trial No.	Steering ratio		Time delay, s	Steering wheel drift, deg/min clockwise
	at 0,1 Hz	at 0,6 Hz		
1	9,3 : 1	10,0 : 1	0,04	49
2	9,9 : 1	12,5 : 1	0,06	7,5
3	12,2 : 1	12,8 : 1	0,14	7,5
4	11,1 : 1	11,1 : 1	0,08	7,5
*	8,3 : 1	11,2 : 1	0,14	28

* Static laboratory trial

Table 5. Frequency response – dynamic conditions.
Frequenzverhalten – dynamische Bedingungen.

3.4 Steering wheel drift

The last column on this table shows a feature which is well known to users of hydrostatic steering systems. The asymmetrical response between left and right hand turns results in the steering wheel returning to different positions every time the front wheels return to the straight ahead position. In this way the steering wheel gradually rotates, or drifts, as the tractor is driven along. The amount of this rotation naturally depends on the amount of steering movement. A value of 49 deg/min was obtained for very artificial conditions, but even 7,5 deg/min found under quite normal conditions is still surprisingly large.

4. Conclusions

The results presented here show that the steering ratio for a tractor hydrostatic steering system is far from constant, and can vary by at least as much as 9,5 : 1 to 14,5 : 1 depending on operating conditions and the type of steering movement. There is also a delay in such a system which may vary between 0,04 s and 0,14 s. There may also be a tendancy for the steering wheel to drift or rotate slowly while the tractor is in motion and not provide a fixed reference to indicate to the driver when the wheels are straight ahead.

The results suggest that any method to be used for comparing steering systems should use dynamic steering demands with the tractor in motion.

First results from our main experiments on steering accuracy [2] suggest that the hydrostatic system does sometimes have a bad effect on accuracy, but further trials are needed to confirm this.

The hydrostatic system of steering has many advantages for agricultural tractors. The physical workload on the driver is light. The noise transmitted into the cab is small. The designer has greater freedom in deciding where components may be placed than he has when there is a direct mechanical linkage. The features which we have measured do not have any importance themselves. But if we find that drivers cannot achieve maximum accuracy with this type of system, then we need to consider improvements. Then these measurements will provide a basis for comparing new systems.

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