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The influence of different steering systems on a wheel slip

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ABSTRACT

Purpose: Modern and advanced mountain tractor allows four different modes of steering wheels: front wheels, back wheels, four wheels and crab steering. The current paper presents the impact of different ways of steering to control the slip in the work transverse on the steep hill slope (39.08%).

Design/methodology/approach: For each mode of steering eight measurements were made; four measurements at a forecasted speed of 0.69 m/s and four measurements at a speed of 1.39 m/s. During the two of four measurements the travelling direction was from the left to the right, and vice versa.

Findings: The measured slip depended significantly on the steering system, while the driving direction did not cause any differences in the slip.

Research limitations/implications: The experiment results presented herein can be applied only with the similar mountain tractors, which allows four different modes of steering wheels. Additional limitation represents the working polygon and the growing conditions of grass.

Practical implications: The crab - steering resulted in the smallest slip (5.96%) at the average driving speed of 1.08 m/s. When steering with all four wheels, the slip at the average speed of 1.03 m/s increased to 7.27%. The biggest slip was measured when steering with only front wheels was applied. In this case the slip was 8.07% at the average speed of 1.01 m/s.

Originality/value: The findings from our experiments indicated that it is very useful to have all wheels steering tractor when working on step slope, because it is grass friendly, offers bigger agility of tractor and improve the safety of the operator.

Keywords: Technological devices and equipment; Machines; Mountain tractor; Mower

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1. Introduction

Stability problems arise with all types of machinery which travel on sloping land. Overturning accidents cost time and money as well as causing injury and sometimes death [1].

The majority of agricultural tractor overturning accidents on slopes are of two types. The first, known as a stability loss accident, is when the tractor overturns directly, and the second, known as a control loss accident, is when the tractor runs away out of control before overturning [2].

Mountain tractor is especially designed tractor to work on sloping ground where there is no longer possible to secure the use of a standard tractor. It is distinguished by a very low clearance and very low height of centre of gravity. Wheel distance is large, which means additional stability in the work on the steep slope. Tractors drive on all four wheels with the same size. The development of those tractors began after the Second World War, however the first commercial vehicle was the AEBI's Terratrac TT77 from 1976 [3].

In vehicle dynamics, slip is the relative motion between a tire and the road surface on which the wheel is moving on. This slip can be generated either by the tire's rotational speed being greater or less than the free-rolling speed (usually described as *percent* slip), or by the tire's plane of rotation being at an angle to its direction of motion, referred to as slip angle [4-8] measured in a field experiment with a mechanic and hydrostatic version of the AGT 835 T tractor a slip during empty travelling uphill and downhill. In empty travelling uphill, the slip in mechanic transmission reaches up to 10%, while about 2% lower slip was measured in the hydrostatic tractor. In travelling downhill, the force of gravity predominates, thus negative slip (-6%) was measured. Owing to sliding caused by gravity, the distance travelled by a tractor wheel was shorter than the distance actually travelled by the tractor along the trail.

Since there are no precise investigations about the slip during the transverse travelling on the steep slopes with mountain tractors, our research was focused on the affect of different steering methods on the slip during the work on a meadow. Three various control methods and their impact on the slip during the work on the slope is presented in the following chapters.

2. Description of the approach, work methodology, materials for research, assumptions, experiments etc.

The driving speed and slip of tires presented in this article are the outcome of field experiments carried out on the research meadow close to the town Sevnica, Slovenia (46° 3′ 20.44″ N, 15° 12′ 29.98″ E) owned by the local farmer Golob. The measuring site is located on a pasture called "Above the road." with the average altitude of 343.945 m and the average slope of 21.345 m, which is equal to 39.079%.

The air temperature was 21°C at 10.00 A.M. and 31°C at 3.00 P.M. after we finished the experiment. The ground was dry and free of dew; base polygon measurement was the same (with the exception of repressed grassland) during the all measurements. The task of a tractor driver was to drive constantly with a steady speed. In fact, the tractor driver had to drive as little maneuver at the top mark band, at a distance of approximately 5-20 cm of the strips, while it could not rely in direction.

In the field experiment front wheel steering, four wheels steering and crab-steering were testing during travelling transverse on the slope. Fig. 1 represents four different steering system, which are available in modern mountain tractors

For each mode eight measurements were made. It means that four measurements at a forecasted speed of 0.69 ms^{-1} (2.48 kmh^{-1}) and four measurements at a speed of 1.39 ms^{-1} (5.00 kmh^{-1}) were researched. During the two of four measurements the travelling direction was from the left to the right, and vice versa.

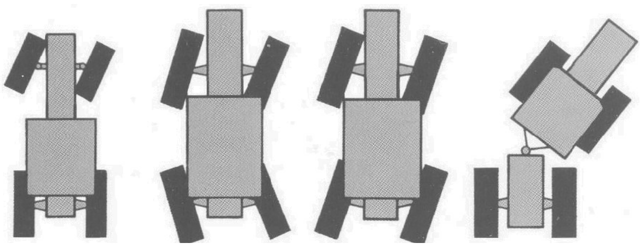

Fig. 1. Different steering systems from left to right; common front wheel steering, four wheel steering, crab-steering, central steering [10]

The polygon (Fig. 2) has been divided into four zones; each of them had a width of 4 m and a length of 40 m. The polygon has been pre-cleaned cut and the grass was mown from the meadow. We fixed the sticks into the ground at each end and the middle path dug by hammer, or otherwise we just lay them on the site measured at intervals of five meters. At the end of each band there was a place for manoeuvring, in which the slip measurements did not perform. The yellow arrows indicate the travelling direction to the right, and the red arrows indicate the travelling direction to the left.

a)

b)

Fig. 2. Design of the experimental field (a) and the test tractor (b)

A mountain tractor Reform Metrac 2003 (Fig. 3) with a 22.4 kW engine and a mass of 950 kg was applied in the experiment. The maximum allowed total weight of the tractor-coupled connections on the front and back was 1450 kg; wheelbase 1580 mm, width of the mid-to mid tires 1590 mm and width of the outer edge of the left tire to the outer edge of the right tire 1910 mm.

Fig. 3. A mountain tractor Reform Metrac 2003 used in the experiment

During the measurements, the mower REFORM (Fig. 4) with a working width of 194 cm was coupled on the front three-point connecting only to simulate the additional weight during usual mowing.

In the simulation of mowing a time was measured with a stopwatch, the real traveled path by using a measuring wheel and the number of turns the drive wheels trigger to the counters.

Statistical analyses of results obtained in our field measurements performed using the Package Program 16.0 (SPSS Inc.) [9].

Fig. 4. A double blade mower REFORM applied in our experiment

2.1. Path and slip measurements

Before calculating the slip we had to measure the actual length of travelling with so called fifth wheel and compare it with the length travelled by each tractor wheel.

When purchasing counters we wanted to ensure the precision of distance measurements to 1.0 m accuracy. We bought meters produced by a Twins manufacturer. Counter with a precision of 1.0 m is in one revolution of the wheels recorded at 1.

For this purposes inductive cycling counters (Fig. 5) were installed to measure the driven distance of each wheel separately, whereby the original 1 magnetic rim was replaced with 8 rims. On that way, we improve the original accuracy of measurements from 1.00 m on 0.25 m.

Fig. 5. Cycling counter fixed on the dashboard

Magnets are needed to trigger the sensor inductive current. Every time an individual magnet rotates past the sensor, the sensor coil inducing a slight tension, which causes the meter, detects this and the latter appears in the form of numbers on the screen. In our case, this means that lists every parade magnet number +1.

The installation of the sensor and the magnet on the wheel is represented in the Fig. 6.

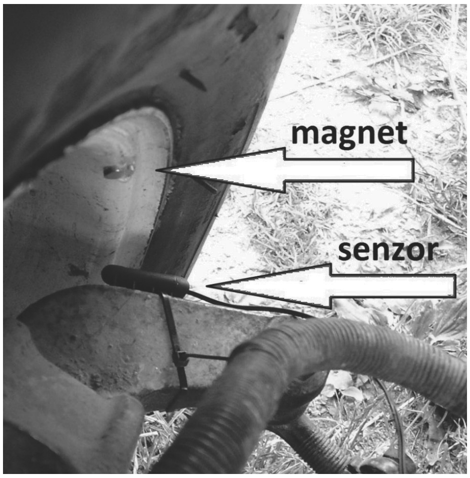

Fig. 6. Installation of sensor and magnet on the wheel

Additional equipment used in the experiment represent; hot gluing gun, which was used for assembling magnets on the rim and assembling counters on the dashboard of the tractor (Fig. 5). Measuring tape was used for estimating the length of the probe measuring polygon 40 m, in the accuracy of 1 mm. We needed to precisely define the size of the polygon and to indicate the control points with wood panels. Those panels were the basic elements to indicate the driving path on the meadow.

2.2. Analysis of a travelled path and slip

Before quantifying the travelled path in each driving mode we have to measure the circumference of the NANCO 26x12-12 tire, first described in [11,12]. Then we calculated actual circumference (cm) based on the test data according to the following equation:

$$\text{Tire circumference} = \frac{\text{number of magnets on a wheel} * 2000}{\text{average data of all counters}} \quad (1)$$

Since the actual and theoretical paths differ, because of the slip, we estimated the average error during the each test measurement with the next equation:

$$\text{Average error} = \frac{\text{average of four measurements} * 100}{\text{theoretical average (without sleep)}} - 100 \quad (2)$$

The driving speed (ms^{-1}) was calculated mathematically from the length of the polygon (m) and the time spent (s) for each repetition separately according the following formula:

$$\text{Speed} = \frac{\text{lenght of the polygon}}{\text{time}} \quad (3)$$

If we wanted to calculate the actual travelled path (m) we had to consider the slip. For this reason the following formula was applied:

$$\text{Actual traveled path} = \frac{\text{counter data} * \text{tire circumference}}{\text{number of magents on the wheel}} \quad (4)$$

Finally, we can calculate the coefficient of the slip according the following well known formula:

$$\delta = 1 - \frac{s_s}{s_t} \quad (5)$$

where:
s_s ….path travelled with slip;
s_t ….theoretically travelled path without slip.

3. Description of achieved results of own researches

Based on the data obtained in the experiment the following features were calculated:

- tire measurements,
- average speed in each repetition (ms^{-1}),
- traveled path of the drive wheels, which include the slip (m) and
- the average wheel slip for each steering system (%).

3.1. Tire measurements

The circumference of the measured tire during driving on the 20 m long asphalt surface as well as the number of turns on counters is represented in the Table 1. As seen the number of turns deviated from 80 to 81, which means only for one pulse i.e. 0.25 m. The most correct results were obtained for the front right wheel (80), followed by the both left wheels (80.33) and the rear right wheel (80.66). According to test measurements, we concluded that there were systematic errors due to the initial position of magnets and not because of the measuring equipment. The second part of the error occurs because the tractor drivers did not stop always in the same position (indentation few inches can increase or decrease the value recorded in a given display meter).

Based on the Equation 1 the calculated circumference of the tire type NANCO 26x12-12 was assumed as 199.17 cm. The average error is calculated by equation 1 and a relevant range tires 200 cm, is 0.41%.

Table 1.
Results of the tire measurements

	Test path [m]	Counter front left	Counter rear left	Counter front right	Counter rear right
Repetition 1	20	80	81	80	80
Repetition 2	20	80	80	80	81
Repetition 3	20	81	80	80	81
Average	20	80.33	80.33	80.00	80.66

3.2. Slip at crab-steering

When driving in a crab-steering we expected a minimum slip, since the manufacturers point out that this control mode is well suited for extreme slope [13,14]. We wanted to know what an impact the speed of driving caused on the slip of individual wheels has, when crab-steering. From Tables 2 and 3 we can see that the slipping of the wheels on the front is smaller.

The actual travelled path of each four wheel during the crab-steering system is represented in the Table 2. On the 40 m long polygon the longest actual travelled path was measured on the rear left wheel (42 m), followed by front left and front right wheel (41.75 m). The shortest actual path was detected on the rear right wheel (41.25 m).

The slip at crab - steering is represented in the Table 3. As seen, at a speed of 0.68 m /s the largest slip was measured on the front right wheel (6.26%), followed by the left front wheel (5.94%). Contrary, the smallest slip was measured on right rear wheel, namely 3.75%. With the increasing travelling speed, the average slip increased from 5.00% to 8.12%, due to the increase in slip on all wheels, At a speed of 1.46 m/s the maximum slip (10.94%), was on the front left wheel and the smallest on the front right wheel of (5.31%).

Table 2.
Field data from crab-steering

Steering	Time [s]	Polygon length [m]	Actual travelled path front left [m]	Actual travelled path rear left [m]	Actual travelled path front right [m]	Actual travelled path rear right [m]	Actual travelling speed [kmh^{-1}]
Crab-steering forward 1	63	40	41.75	42	41.75	41.25	5.33
Crab-steering backward 1	63	40	41.25	42	42	41.25	5.33
Crab-steering forward 2	62	40	43.25	43.25	42.25	42	5.14
Crab-steering backward 2	65	40	41	41	42.25	42	5.33

[1] forseen speed 2.48 kmh^{-1}, [2] 5.00 kmh^{-1}

Table 3.
The slip of each wheel at crab-steering travelling mode

Steering	Speed [m/s]	Slip Front left [%]	Slip Front Right [%]	Slip Rear Left [%]	Slip Rear Right [%]	Slip Average [%]	Slip [m]
Crab-steering 1	0.68	5.94	6.26	4.06	3.75	5.00	2.00
Crab-steering 2	1.47	10.94	10.63	5.31	5.63	8.12	3.25

Table 4.
Field data from four wheel steering

Steering	Time [s]	Polygon length [m]	Actual travelled path front left [m]	Actual travelled path rear left [m]	Actual travelled path front right [m]	Actual travelled path rear right [m]	Actual travelling speed [kmh^{-1}]
Four wheel forward 1	60	40	42.5	42.5	41.5	41.75	2.4
Four wheel backward 1	63	40	41	41.5	42.75	42.75	2.28
Four wheel forward 2	62	40	44.5	44	42.25	42.25	2.28
Four wheel backward 2	65	40	41.75	41.5	43.5	43.25	2.28

Table 5.
The slip of each wheel at four wheel steering mode

Steering	Speed [m/s]	Slip Front Left [%]	Slip Front Right [%]	Slip Rear Left [%]	Slip Rear Right [%]	Slip Average [%]	Slip [m]
Four wheel steering 1	0.64	8.75	8.13	4.69	5.00	6.64	2.66
Four wheel steering 2	1.42	12.81	12.81	5.00	5.63	9.06	3.63

3.3. Four wheel steering

It is known that during a four wheel steering the minimum turning radius is required and therefore the tractor is most versatile [15]. The actual travelled path of each four wheel during the four wheel steering system is represented in the Table 4. On the 40 m long polygon the longest actual travelled path was measured on the rear front wheel (43.2 m), followed by rear right (43.25 m). The shortest actual path was detected on the front left wheel (41.00 m).

However, as seen from Table 5, the slip is higher than in the crab-steering for 1.64% at a speed of 0.64 m/s and for 0.94% at a speed of 1.42 m/s respectively.

Table 5 shows that the difference in slip between the left and right wheels at operating speed and steering all four wheels on average increased by more than a single value.

The highest slip at a speed of 0.68 m/s was measured on the front wheels like in the crab-steering mode; on the front left wheel (8.75%) and on the left front wheel (8.13%) (Table 6). Contrary, the smallest slip was measured on left rear wheel, namely 4.69%. With the increase in the travelling speed to 1.42 m/s, the average slip increased from 6.64% to 9.06%, due to the increase in slip on all wheels. So the maximum slip (12.81%) was on the both front wheels and the smallest on the left rear (5.00%).

3.4. Front wheel steering

Front wheel steering uses most of the tractors. This steering gives the best balance between the price and utility. Manoeuvrability is satisfactory, but the problem is that the front wheel steering intended to work with towed terminals and connectors coupled to the rear three-point connection, is rather easier than working with end connectors. In steering of the front wheels, the rear wheels are aligned and not feeding. A coefficient of slip is represented in the Table 7 and has been calculated using the Equation 5.

Front wheel steering is commonly applied on all agricultural tractors; however it is not convenient for travelling on the steep slopes. In our experiment with steering of the front wheels the rear wheels were aligned and fixed.

Table 6.
Field data from front wheel steering

Steering	Time [s]	Polygon length [m]	Actual travelled path front left [m]	Actual travelled path rear left [m]	Actual travelled path front right [m]	Actual travelled path rear right [m]	Actual travelling speed [kmh^{-1}]
Front wheel steering forward 1	63	40	44	43.75	41.75	41.75	2.28
Front wheel steering backward 1	64	40	41.75	42	43.75	43.25	2.25
Front wheel steering forward 2	65	40	45.25	45.25	42.50	42.75	2.18
Front wheel steering backward 2	61	40	41.25	41.25	43.25	43	2.36

Table 7.
The slip at front wheel travelling mode

Steering	Speed [m/s]	Slip Front Left [%]	Slip Front Right [%]	Slip Rear Left [%]	Slip Rear Right [%]	Slip Average [%]	Slip [m]
Front wheel steering 1	0.63	11.56	11.25	5.31	5.63	8.44	3.38
Front wheel steering 2	1.38	15.94	14.38	4.06	6.25	10.15	4.06

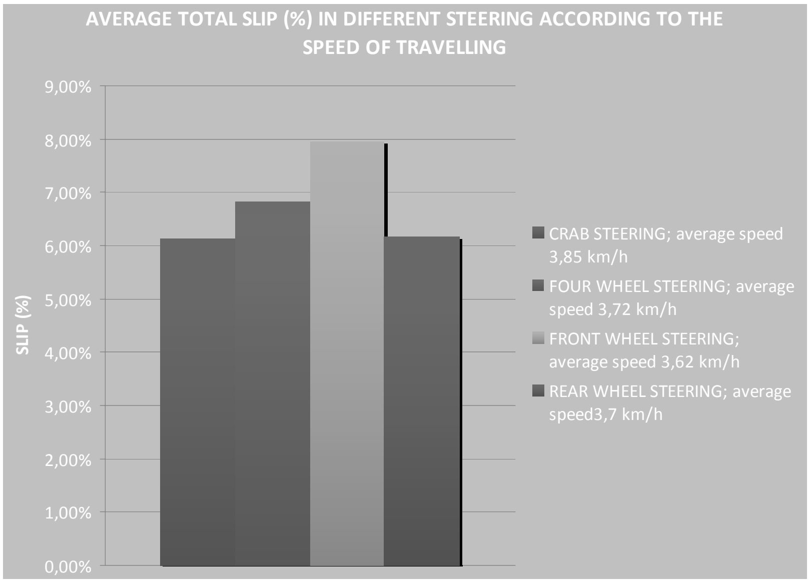

Fig. 7. Average slip in all steering system during the experiment at two travelling speed

All the bed characteristics of such steering can be seen in Table 7, because the slip increased on all four wheels in comparison to four wheel steering. On the average the total slip was higher for additional 1.80% at a speed of 0.63 m/s and for 1.07% at a speed of 1.38 m/s, respectively. Again the highest slip at a speed of 0.68 m/s was measured on the front axe; left wheel (15.94%) and right wheel (14.38%). Opposite to the four wheel travelling, the slip on the both rear wheels decreased on 4.06% (left) and 6.25% (right).

This happened because the front wheel steering of both front wheels turn did not have enough friction to turn in the desired direction and the tractor did not turn in that direction without problems. In doing so leads to increased slip of the wheels. However, since the right front wheel in this case is loaded beyond the left front wheel, due to the impact of increased slip differential to less loaded bikes.

4. Conclusions

In our field experiment with the mountain tractor REFORM METRAC 2003 three different steering modes was research on the meadow with an average transverse slope of 39.08%. The smallest slip of all modes 5.00% was measured during the crab-steering at the speed of 0.68 m/s. On average it was 1.64% less than during the steering of the front wheels and 3.44% less than during the front steering mode. The average slip in all steering system during the experiment at two travelling speed is represented in Fig. 7.

Although the crab steering indicated the smallest slip, our control tractor was not equipped with the automatic system for travelling in this specific mode. Therefore the operator consumed too much time for switching the rear wheels on, because the tractor had to stop each time. Another option represents tractors, in which sensors monitor wheel position. In this case, tractor driver only presses a button on computer command to switch between different modes of controlling the wheel position without stopping. These solutions are really user-friendly; however Slovenian farmers can not afford it, because the prices are enormous high.

From those reason the control of all four wheels use to be optimal solution for operating in the slope during mowing, hay processing and collecting. However, in this driving mode the average slip at a speed of 0.64 m/s was 6.64%, which is higher than in crab steering and less than during steering of only the front wheels. The control of all four wheels is the most applied travelling on the Slovenian steep meadows, as there is no switching between different modes of control. For example, when the front wheels are turn left, we turn the rear wheels to the right. This results in extremely small turning circle, high productivity at work and low physical and mental load of a tractor driver. Again, that control requires additional cost of mountain tractors in comparison with a common agricultural tractor.

Steering front wheel had at a speed of 0.63 m/s an average slip of 8.44%. This means that the wheels travelled at a 40 m experimental field 3.38 m distance longer, because of the slip. This does not sound a lot, however a slip is sufficient enough for the destruction of green cover, especially, if we know that the grass has to be turned, gathered and got down to the valley. This control mode was especially suitable for working with back connected to the three-point connecting in the past. However, the connectors at the front three-point system is not suitable for travelling transverse on the slope, because the whole rigid weight of the mower increases the slip-up of the front wheels.

Since the current high prices of mountain tractors do not allow farmers to buy it, a fruit growing tractors became more and more popular substation. A good example is a tractor AGT model 850. This tractor is only able to control the front axle, but the weakness of front wheel steering only can be resolved otherwise. The tractor is reversible and when we turn to sit, the last front three-point system becomes the first one, so in this case it is controlled by the rear wheels. We assume that this has control at work in the lower slope slipping as steering the front wheels. The most enticing feature of the tractor 850 AGT is its price.

The reason for smaller price lies in the engine power since in mountain tractors there is much higher impact on price as the standard. Therefore, anyone who decides to buy such a tractor soon is going to ask at what extent the tractor will work. It should be noted that the power increases by the tractor aunt. If the tractor is working on a small farm and will be used only for grassland tasks such as mowing, turning and making hays, it makes no sense to buy a tractor with more than 35 kW. But if the aim of the tractor will be baling, delivery of slurry, collecting the trailer loading, etc., then it is necessary to purchase in mind and buy a tractor, which will also have a strong enough engine, even enough own aunt.

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