CAGE WHEEL TRACTIVE PERFORMANCE OF 4WD TRACTOR IN PADDY FIELD
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PENGUJIAN TRAKSI RODA SANGKAR TRAKTOR RODA EMPAT DI LAHAN SAWAH

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ABSTRACT
In Indonesia, the use of four-wheel drive (4WD) tractors in paddy fields has been introduced, replacing two-wheel tractors. However, the condition of Indonesian paddy fields is commonly deep due to the absence of hard pan layer that make lower tractive performance of 4WD tractors. This research designed a special cage wheel for a 4WD tractor and compared it to a commonly used rubber wheel. The result showed that the cage wheel could increase the drawbar pull by 39.5% and drawbar power by 66.2%. It could also reduce wheel slippage by 21.9% and decrease sinkage by 15.9%.

ABSTRAK
Di Indonesia, traktor roda empat tengah diintroduksikan untuk menggantikan traktor roda dua. Namun, kondisi lahan sawah yang dalam membuat kinerja traksi traktor roda empat menjadi rendah. Penelitian ini bertujuan untuk mendesain roda sangkar dan membandingkan kinerjanya dengan roda karet yang umum digunakan di traktor roda empat. Hasil menunjukkan bahwa roda sangkar meningkatkan drawbar pull 39.5% dan drawbar power 66.2%. Roda sangkar ini juga mampu menurunkan slip roda sebesar 21.9% dan ketenggelaman sebesar 15.9%.

INTRODUCTION
Lately, in Indonesia, there has been a noticeable shift towards the adoption of 4WD within paddy fields, replacing the previously dominant two-wheel tractors. Yet, this transition to 4WD tractors has brought forth a significant challenge - the notably deep condition of the paddy fields, attributed to the absence of hardpan layers (*Jusran et al., 2019*). In narrow muddy paddy fields, general agricultural machinery is difficult to show good performance (*Chen et al., 2020*). Moreover, the depth of mud tends to increase year by year due to the deposition of soil brought by high mud content in irrigation water.

The absence of a soil hardpan makes difficult trafficability for any machines for crop maintenance (*Setiawan et al., 2013*). Wheel sinkage is a common problem occurred in tractors or other machinery in a wet deep paddy field in Indonesia. The sinkage of agricultural machinery has been the topic of intensive research in the past and will continue to be in the future (*Pradhan et al., 2015*). Insufficient shear resistance in paddy soil often leads to sinking, slipping, or even the inability to travel (*Chen et al., 2024*).

One of the efforts to provide better traction and trafficability for an agricultural tractor is by using a cage wheel. Implementing a cage wheel on a two-wheel tractor holds the potential to significantly enhance the traction performance of the tractor when operating in a wet paddy field (*Eswari et al., 2018*) as well as in wetland cultivation (*Pradhan et al., 2016*). In Indonesia, cage wheels have been commonly used for two-wheel tractors and commercially available in the market. However, cage wheel for 4WD tractors has just been introduced, so there is no academic paper yet on how cage wheels can improve the tractive performance of 4WD tractors compared to standard rubber wheels. Therefore, this research intended to compare the performance of the cage wheels which were specifically designed for 4WD tractors with rubber wheels.

The cage wheels are made using heavy-duty angle and iron & steel material (*Kumar et al., 2018*). Tractive performance depends greatly on the dimensions, shapes, and materials of the wheels used and the soil conditions (*Nizamani and Cebro, 2018*). The cage wheel provides a floating effect to power tiller in wet paddy fields, in addition to puddling the soil (*Pradhan and Verma, 2017*).

The aim of this research was to design a special cage wheel for a 4WD tractor, assess its tractive and trafficability performance, and subsequently compare it with the performance of a standard rubber wheel of the 4WD tractor.

MATERIALS AND METHODS

- **Cage wheel design and prototype**

The cage wheel tested in this research was specially designed by Yanmar Agribusiness Co. Ltd. Japan for Yanmar Tractor EF453T series. The main design criteria of cage wheel were that the cage wheel could provide a good traction force as well as lifting force to support the vehicle against sinkage, and the lugs arrangement could prevent soil blocking between lugs in wet paddy field. Based on these criteria, "V" shape lugs were selected to provide a good traction for forward as well as reverse travel direction. Moreover, "V" shape lugs had lower effect of destroying the hard pan of paddy field. The optimum number of lugs of the designed cage wheel was 12 lugs, with 150 mm width of forward lug face and 80 mm width of reverse lug face. Lug angle of forward lug face was 35^o, while for reverse lug face was 45^o. The weight of one cage wheel was 164 kg and overall dimension of the designed cage wheel is shown in Figure 1.

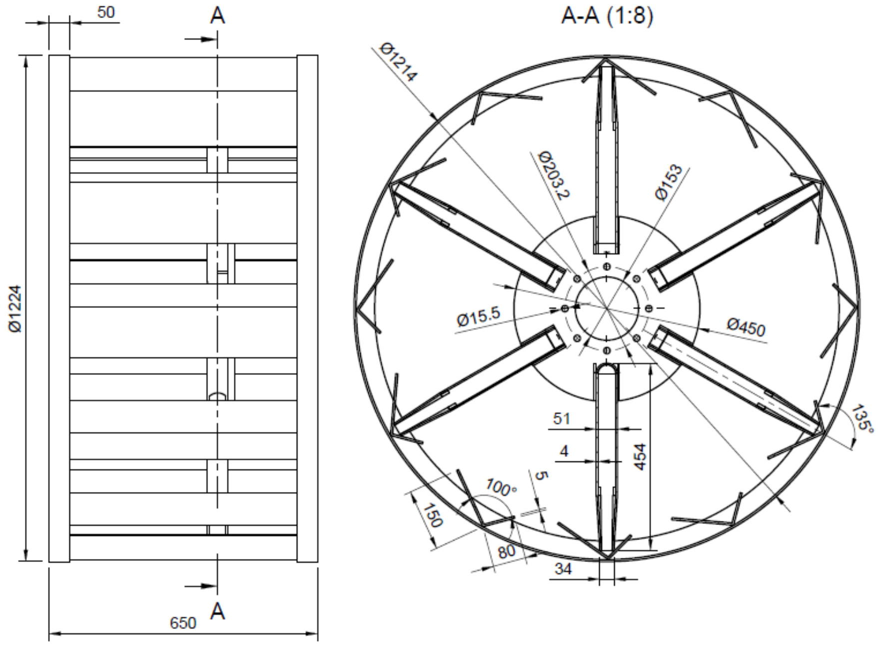

Fig. 1 – Cage wheel design

The prototype of cage wheel was manufactured by Yanmar Agricultural Research Institute - IPB University Indonesia. Given the prevalent absence of farm roads connecting paddy fields in Indonesia, a pragmatic approach was taken. In this regard, 12 pairs of supplementary small lugs were strategically affixed to the outer rim of the cage wheel, as visually depicted in Figure 2. Those additional lugs were designed to improve the cage wheel traction especially when the tractor is traveling between paddy field borders.

Fig. 2 - Cage wheel prototype installed on the tested tractor

- **Location and equipment**

The performance test was taken place in the Department of Mechanical and Biosystem Engineering, IPB University, Indonesia. The performance tests for cage wheels and rubber wheels were carried out on the same paddy fields. The size of the paddy fields was 30x30 m and divided into two, half was used for measuring the performance of the cage wheels and the other half was used for measuring the performance of the rubber wheels. Land preparation of the test field was done using two passes of rotary tiller. Soil cone index was measured before the test and the location for measuring the soil cone index was on the 10x10 m grid as shown in Figure 3. The soil sample of paddy field was also taken before the test for analysing the soil texture classification.

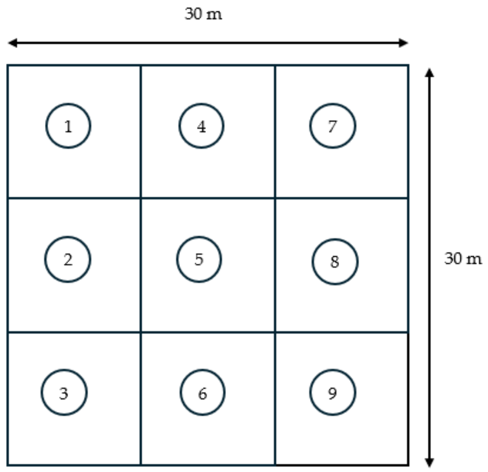

Fig. 3 - Location of soil cone index and soil sampling

The tractor subjected to testing in this research was the YANMAR EF453T, a 4WD tractor with an engine power output of 33.8 kW. Standard rubber wheels of this tractor having size 13.6-26 with 121 cm diameter, 4 ply rating with R-2 lug type and total weight of tractor with rubber wheel was 1450 kg. To determine the drawbar pull of the tested tractor, a KUBOTA L3608, another 4WD tractor with an engine power output of 26.5 kW, was employed as the load tractor. The drawbar pull was measured using a drawbar-type load cell, namely Kyowa LTR-S-SA1, which had a capacity of 5 tons. An ultrasound sensor (Ultrasonic Range Sensor Module HC-SR04) was utilized to measure the tractor's sinkage. Signal data from load cell and ultrasound sensor were recorded in a digital data logger. For the measurement of soil cone index, a digital soil compaction meter named Field Scout SC900 was employed. The tractor’s actual forward speed was measured using a measuring tape and stopwatch.

- **Experimental details**

The parameters included in the tractive performance test were actual forward speed, drawbar pull, drawbar power, and coefficient of traction. While the trafficability performance is expressed by wheel slippage, sinkage, and turning radius. The tractive performance test was measured by following the Indonesian Standard for Tractor Performance Test (SNI 7416:2019) with the setup being shown in Figure 4. Tractor was operated at gear position: main gear 1, secondary gear 2, and engine speed 2000 rpm. This engine speed was selected because it was recommended rated engine speed for long run application by the tractor manufacture.

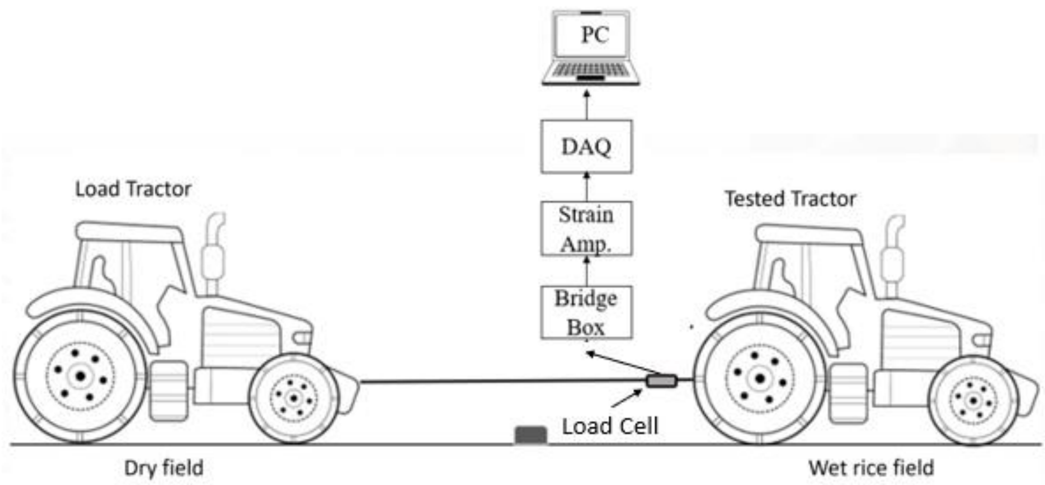

Fig. 4 - Setup of tractive performance test

To calculate tractive performance, Equation 1 and 2 were used (*Macmillan, 2002; Pradhan et al., 2017; Hensh et al., 2022*).

$$P = F \times v \quad (1)$$

where:

P is drawbar power, kW; F is drawbar pull, kN; and v is tractor forward speed, m/s.

$$CoT = F/W \quad (2)$$

where:

CoT is the coefficient of traction and W is the total tractor's weight, kN (*Jusran et al., 2019*). The total tractor's weight with cage wheels was 1536 kg and the total tractor's weight with rubber wheels was 1450 kg. Wheel slippage was calculated by Equation 3.

$$S = (S_o - S_t)/S_o \times 100 \quad (3)$$

where:

S is wheels slippage, %; S_o is traveling distance of five-wheel revolutions on hard surface terrain, m; and S_t is traveling distance of five-wheel revolutions on test field, m.

Trafficability parameter was shown by wheel sinkage as a measure of a wheel's depth below the terrain surface (*Creager et al., 2017*) which was measured by using an ultrasound sensor for distance measurement as expressed in Equation 4.

$$z = d_o - d_i \quad (4)$$

where:

z is sinkage, m, d_o is the distance from bottom of tractor body to the terrain surface in hard soil, m; and d_i is the distance from the bottom of tractor body to the terrain surface during test, m.

The turning radius was defined as the distance from the centre of the outer wheel tread to the point where the tractor completed a U-turn. This measurement was taken using a measuring tape, as illustrated in Figure 5. The duration of performing U-turn was measured by a stopwatch.

Fig. 5 – Setup and field measurement of turning diameter (TD)

RESULTS

- **Test field condition**

Based on soil texture analysis, the test soil was categorized as silty clay according to USDA Soil Texture Classification, that consisted of sand 6.7%, silt 52.2% and clay 41.1%. The high content of silt and clay>40% found in this research was in accordance with the findings of *Fakhiroh et al.*, (*2019*) who stated that soil texture of Indonesian paddy field in the study area was dominated by clay and silt with the clay fraction more than 55%.

The soil cone index result is plotted in Figure 6. Based on this graph, it can be understood that the soil cone index started increasing at the soil depth of 20 cm. Then it began to be stable at the soil depth of 30 cm. This indicates that it already touches the hardpan. This soil depth is commonly found in a wet paddy fields in Indonesia. Seemingly, the depth hardpan layer more than 30 cm was also found by *Guturu et al.*, (*2016*) in the wet paddy field in India.

- **Tractive performance of the cage wheel**

The tractive performance for cage wheel showing relation between wheel slip, drawbar pull and drawbar power is shown in Figure 7. It can be seen from the figure, that the maximum drawbar pull was 11.5 kN at a slippage of 48.2%. The trend shows that after this point the drawbar pull kept constant while slippage tends to increase. The maximum drawbar power 3.2 kW was reached at a wheel's slippage 27.3%.

Soekarno and Salokhe (*2003*) studied that the drawbar power of a power tiller with cage wheel reached a maximum value at 15% wheel slip and then decreased further with the increase of wheel slip. When the slippage increases over the above slip values, the drawbar power decreases to zero at 100% of wheels slip (*Triratanasirichai et al., 1990*). After the maximum drawbar power was achieved, drawbar power tends to decrease because the increment of drawbar pull was lower than the decreasing of forward speed. Thus, since the drawbar power is the product of drawbar pull and forward speed, then the drawbar power was reduced after it reached the maximum point.

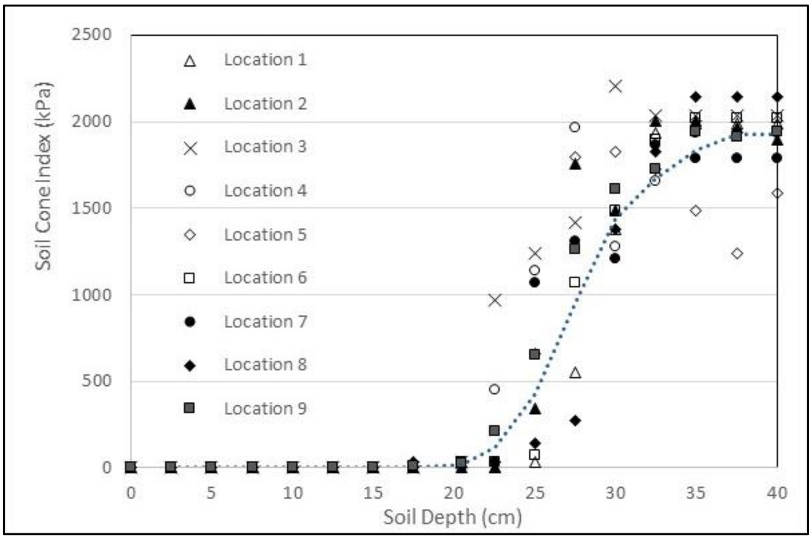

Fig. 6 – Soil cone index graph

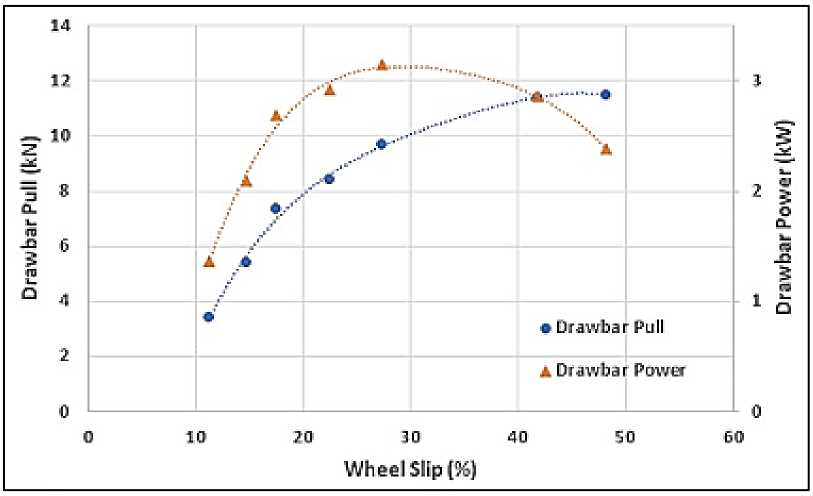

Fig. 7 – The drawbar pull and drawbar power at different wheel slip for cage wheel

The correlation between forward speed and sinkage based on certain slippage is shown in Figure 8. Based on the figure, the forward speed was decreasing with the increase of wheel slip. At the lowest drawbar pull, the wheels slip was 11.2% resulting in the forward speed 0.4 m/s and then the wheel slip continually increased with the increase of drawbar pull thus the forward speed was decreased. For each level of load applied to the test tractor, the sinkage varied slightly, but there was no trend of either increase or decrease with the increase of wheel slip.

This indicates that the cage wheels can provide sufficient lifting force to keep the tractor from sinking. The maximum sinkage was 32.8 cm which occurred at 14.7% and 22.5% wheels slip. *Pradhan et al.,* (*2015*) who studied the effect of sinkage and sticking on a cage wheel attached to a power tiller found that more sinkage and sticking will cause more fuel consumption, more slippage, and reduce speed.

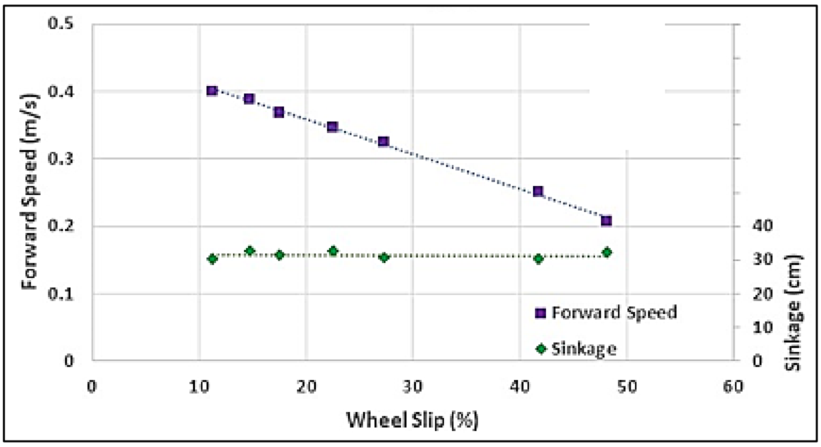

Fig. 8 – The forward speed and sinkage graph at different wheel slip for cage wheel

- **Tractive performance of the rubber wheel**

The result of the drawbar pull, drawbar power, wheels slippage, forward speed, and sinkage of rubber wheel are presented in Figure 9 and Figure 10. Based on the drawbar pull graph of rubber wheel (Figure 9), it shows similar trend to the cage wheel's result in Figure 7. The maximum drawbar pull was 7.7 kN at wheels slip 52.6%. The trend shows that after this slip no more drawbar power can be increased. The maximum drawbar power of 1.9 kW was reached at the wheel slip 35%.

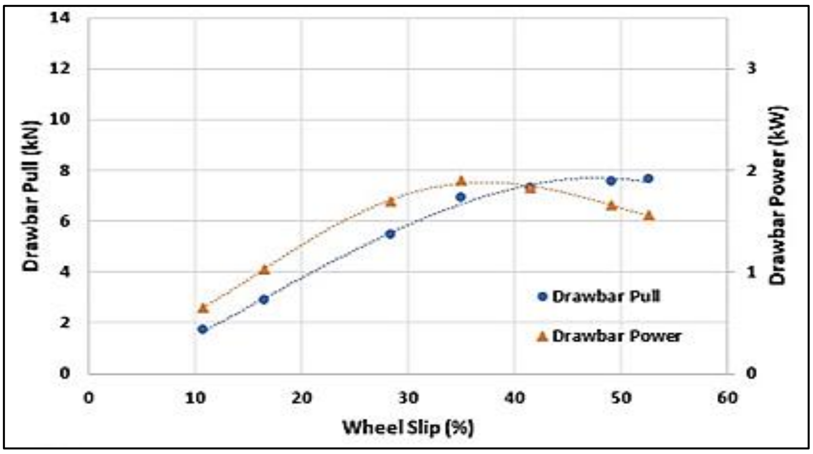

Fig. 9 – The drawbar pull and drawbar power at different wheel slip for rubber wheel

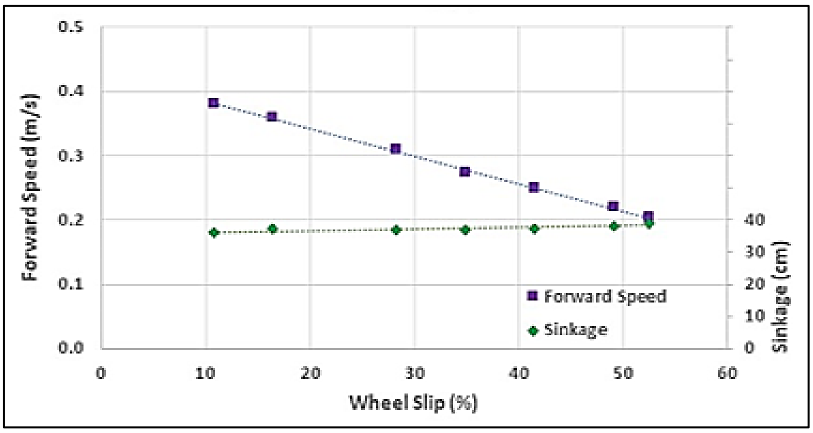

Fig. 10 – The forward speed and sinkage graph at different wheel slip for rubber wheel

The correlation between forward, wheel slip, and sinkage of a tractor with a rubber wheel is shown in Figure 10. The initial wheels slip was 10.8% resulting in the forward speed 0.38 m/s then the wheel slip continually increased with the increasing of drawbar pull thus the forward speed was decreasing. The maximum sinkage was 39.1 cm which occurred at the maximum wheel slip of 52.6%.

- **Comparison of tractive and trafficability between the cage wheel and rubber wheel**

The drawbar pull and drawbar power which resulted from cage wheels (Figure 7) were higher compared with rubber wheel (Figure 9). A higher drawbar pull resulted from the cage wheels was due to the higher traction and shallower sinkage. The condition of shallower sinkage of the cage wheels (Figure 8) was due to higher lifting force of the cage wheel. Consequently, this shallower sinkage will reduce the rolling resistance of the cage wheel. Drawbar pull is a result of traction deducted by rolling resistance.

This shows that the cage wheel gave better tractive performance compared with the rubber wheel. The drawbar performance depends on several factors such as the type of tractor, constructive and operating parameters, and type of the ground (*Nastasoiu and Ispas, 2017*).

According to Figure 8 and Figure 10, the sinkage resulting from cage wheels shows shallower than from rubber wheels. The forward speed of the tractor using cage wheels also resulted to be higher. This was found to be higher because of the presence of the spike on the cage wheels. Those spikes make the diameter of the cage wheels wider thus it increases the forward speed. The sinkage that occurred in the tractor with cage wheels was less because it follows the theory that the usage of cage wheels will give floating action when the lug touches the soil itself. So, it is proven that cage wheels have better sinkage compared to rubber wheels.

At maximum drawbar power as shown in Table 1, the tractive performance of the cage wheels resulted in decreasing wheel slip by -21.9%, higher drawbar power by 66.2%, higher drawbar pull by 39.5%, higher forward speed by 19.1%, and shallower sinkage by 15.9%. The CoT at the tractor using cage wheels is higher by 31.7% compared with the tractor using rubber wheels.

Table 1

Result of drawbar performance test at maximum drawbar power

Wheel type	Wheel slip	Drawbar power	Drawbar pull	Forward speed	Sinkage	CoT
	[%]	[kW]	[kN]	[m/s]	cm	
Tractor with cage wheel (CW)	27.3	3.2	9.7	0.33	30.9	0.64
Tractor with rubber wheel (RW)	35.0	1.9	6.9	0.27	36.8	0.49
Comparison: CW vs RW	**-21.9 %**	**66.2 %**	**39.5 %**	**19.1 %**	**-15.9 %**	**31.7 %**

The trafficability performance of cage wheels and rubber wheels are shown in Table 2. From the table, the cage wheels had a wider turning radius and longer U-turn time compared with rubber wheels. Commonly, cage wheels are more difficult in trafficability aspect. The turning radius and U-turn performance were tested without a brake to make U-turn.

Table 2

The trafficability of the cage wheel and rubber wheel

Wheel type	Turning radius	U-turn time	Sinkage
	[m]	[s]	[cm]
Tractor with cage wheel (CW)	9.3	29.2	32.3
Tractor with rubber wheel (RW)	7.1	25.5	38.7
Comparison: CW vs RW	**31.6 %**	**14.5 %**	**-16.4 %**

The width of the cage wheel was 65 cm while the width of the rubber wheel was 34 cm. For that reason, the total width of the tractor with cage wheel was 237 cm and the total width of the rubber wheel was 161 cm. As the turning radius was affected by the total width of the tractor, the turning radius of tractor with cage wheel become higher.

CONCLUSIONS

Based on the result, it can be concluded that 4WD tractor with cage wheels could provide better tractive performance compared with 4WD tractors using rubber wheels. This was indicated by the increase in drawbar pull, drawbar power, wheel slippage, and coefficient of traction. However, the trafficability result of the cage wheels caused a wider turning radius and longer U-turn time compared with rubber wheels. Sinkage which resulted from cage wheels was shallower compared with sinkage which resulted from rubber wheels.

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