Poster Session | Others (including the category of JSAM and SASJ)
[6-1130-P] Other Categories (6th)
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[6-1130-P-12] Study on Analysis of Loads Effect on Path-Tracking Accuracy of an Autonomous Tractor during Plow Tillage

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Keywords: Agricultural tractor, Lateral error distance, Wheel axle torque, Draft force

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Study on Analysis of Loads Effect on Path-Tracking Accuracy of an Autonomous Tractor during Plow Tillage

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ABSTRACT

The purpose of this study was to provide guidelines for the basic factor of auto-steering system design considering the measured work load on an autonomous tractor during moldboard plow operation. Load of agricultural tractor has been studied intensively, but it is still difficult to analyze the effects of load on the path-following performance of autonomous tractors. The objective of present study was to offer suggestions on measured methods of lateral error distance. The effect of working load such as wheel torque and draft force on the lateral error distance was analyzed. The lateral error distance measurement system consisted of a electric tacheometer, GNSS receiver, and prism. The load measurement system consisted of a wheel torque meter, a telemetric proximity sensor, and 6-component load cells. The field test conducted in a four-wheel mode and an M3-Low gear stage, which are commonly used to perform moldboard plow in Korean paddy fields. The field test was conducted for a 100 m straight line, and the wheel axle torque, draft force, and lateral error distance were simultaneously measured in the same time. Through this field test, the effect of load on the accuracy of path-following performance of agricultural tractor during the plow tillage operation was analyzed. In future study, the field test will be conducted on factors affecting the accuracy of path-following performance among the soil-machine factors. The results of this study can provide useful information to improve the accuracy of path-following performance according to the working load during plow tillage operation.

Keywords: Agricultural tractor; Lateral error distance; Draft force; Wheel torque; Moldboard plow operation

1. INTRODUCTION

The agricultural production and labor shortage issues are constantly increasing due to rural aging (Celik et al., 2018). Agricultural machinery automation is one of the most effective solution of improving agricultural challenges such as food, operating cost, working environment, and so on (Zhang and Pierce, 2013). The global agricultural machinery market is expected to grow at a CAGR (Compound Annual Growth Rate) of 6.6% from US $ 140.7 billion in 2014 to US $ 193.5 billion in 2019 (KREI, 2018). The global autonomous tractors market is expected to grow at a CAGR of 24.8%, reaching 12,508 Units in 2019 and 60,901 Units by 2025. The growth of the autonomous tractor market is expected to lead the government or several primary manufactures as a part of the adoption of new technologies to improve the working efficiency and productivity of crop yields (Li et al., 2019; MarketsandMarkets, 2018). The tractor is main product of agricultural machinery due to various uses as agricultural power source (Kim et al, 2018). Especially, the most important performance evaluation factor of

autonomous tractor is lateral error distance (McCall and Trivedi, 2005). Therefore, the importance of developing autonomous tractor equipped with accurate path-tracking technology for securing competitiveness of the global market is increasing. In addition, the research on the performance evaluation method of path-tracking accuracy has been actively carried out.
In order to improve the convenience of farmers and crop productivity, many studies have been conducted various autonomous agricultural machinery. Some studies related to the autonomous agricultural machinery have been carried out in relation to path-tracking performance considering lateral error and heading angle on off-road surface without tillage operation. The study has been conducted on methods for estimating a utility and agricultural vehicle's dynamic parameters using a RTK-GPS and Inertial Measurement Unit (IMU). The results showed that the measured data using a RTK-GPS and IMU can be used to estimate the tire sideslip and the tire cornering stiffness under different soil conditions (Ospina and Noguchi, 2016; Ospina and Noguchi, 2018). Liu et al, (2019) studied the image processing based UAV (Unmanaged Aerial Vehicle) used for spraying pesticides and herbicide. The results show that the proposed algorithm has more accurate path-tracking performance than DGPS based UAV. Yin et al, (2018) developed an autonomous navigation system using sensor fusion algorithm that automatically guided a rice transplanter working along predetermined paths including steering, stop, going forward and reverse. The results showed that path-tracking were robustly executed in terms of following straight paths. Rahman et al, (2019) developed an optimum harvesting area of a convex and concave polygon for path planning of robot combine harvester. The results show that this developed algorithm estimates the optimum harvesting and reduces crop losses. It is also calculated based on the corner vertices minimizes the total operation time. In another study, the leader follower system was developed using two autonomous tractors for agricultural operation (Zhang and Noguchi, 2017). This experiment results showed the two autonomous tractor can work safely to complete the operation, and the system's efficiency improved by 95.1% compared with using a single tractor. In another study, an adaptive turning algorithm for a four-wheel autonomous tractor was developed using navigation sensors consisted of an inertial measurement unit and a real-time kinematic global positioning system (Wang and Noguchi, 2018). The results showed that the time consumption and turning trajectory were decreased by 17% and 21%, respectively, compared to a conventional turning algorithm. There have been many studies on the automatic steering system of agricultural machinery. These performance evaluation method only using the posture and position information which are logged on the IMU and GPS in the path-tracking performance evaluation has been performed. This method is a performance evaluation method widely used in the automotive field. Generally, an autonomous commercial vehicles drive on a standard road surface such as asphalt without disturbance. However, an agriculture tractor have a relatively high load due to tire slip, sudden change in attitude angle, soil resistance, etc., depending on the correlation between soil and attachment implement during tillage operation (Wong, 2008). This does not take into account the error on the GPS sensor, and therefore it is not an accurate performance evaluation method. In addition, performance evaluation was performed by simple driving without tillage operation which can be used as a representative use purpose of actual farm machinery. The performance evaluation method of the path-tracking accuracy of an autonomous tractor under no tillage operation condition is did not consider the effect of the work load according to the terramechanics factors between soil and the agricultural tractor with attached implement. The load of the agricultural machinery is an important indicator of farming characteristics, and performance evaluation of agricultural machinery through load analysis is essential (Nahmgung, 2001). Therefore, it is necessary to study the new performance evaluation method from the viewpoint of work load which is generated on tractor's main part under tillage operation conditions.

To improve the quality of the tractor, it is necessary to analyze the tractor working load during operation. This is because the work load characteristics are affected by various factors such as soil properties, operation type, traveling speed (gear selection), tillage implement shape, and tillage depth. Load analysis of agricultural tractor during field operation is important in achieving the optimum design of tractors.
Many studies have been carried out in consideration of soil properties, the type of operation, and the seasonal conditions. Analyzing the above research literature to date related to the work load of agricultural tractor during field operation, it can be confirmed that work load has the greatest influence on field operation. Nevertheless, there has been no consideration of precise lateral error distance methods according to work load. Therefore, it is necessary to develop a improved method of lateral error distance measurement and to analyze accuracy of path-following performance according to the work load.
The purpose of this study was to provide guidelines for the basic factor of auto-steering system design considering the measured work load on an autonomous tractor during moldboard plow operation. The specific objectives were (1) to develop a load measurement system and the path-tracking performance evaluation system, (2) to measure the load of the tractor's main part and lateral error distance, (3) to analyze the effect of an agricultural tractor's load on path-tracking performance during moldboard plow operation.

2. MATERIALS AND METHODS

2.1 Agricultural tractor and implement

A 78 kW-class agricultural tractor (S07, Tong Yang Moolsan, Gongju, Korea) was used in this field experiment. The tractor had an empty vehicle weight of 3985 kg and dimensions of 4225 × 2140 × 2830 mm (length × width × height) except for attached measurement system. The tractor used for measurement was equipped with a mechanical transmission. The 32 forward and 32 backward traveling speeds of the tractor were determined by the combination of the gear setting according to the operation type. The rated engine power of the tractor at an engine revolution speed of 2300 rpm was 78 kW. In this study, an eight–row moldboard plow (WJSP–8, WOONGJIN MACHINERY, Kimje, Korea) was used to account for the 78-kW tractor engine power. Moldboard plows are mainly used in Korean rice paddy fields during primary tillage. The moldboard plow is superior to other plow implements in terms of stability; but features relatively large traction resistance. The specifications of the agricultural tractor used in this study are given in Table 1.

Table 1. Specification of the 78-kW agricultural tractor.

Item		Specification
Length × Width × Height (mm)		4225 × 2140 × 2830
Weight (kg)		3985
Engine	Rated power (kW)	78 @ 2300 rpm
	Max. torque (Nm)	430 @ 1400 rpm
Transmission	Main	4 stages and power shift (High, Low)
	Sub	4 stages

2.2 Lateral error measurement system

The lateral error measurement system was built to measure the lateral error distance and the traveling speed of tractor. First, the lateral error distance was measured using an electric tacheometer (iX series, TOPCON, Tokyo, Japan), a GNSS receiver (GCX3, TOPCON, Tokyo, Japan), and a prism attached to the tractor cabins at the center of gravity position. The electric tacheometer was used to evaluate the accuracy of the steering system of the autonomous tractor.

Second, the traveling speed of the tractor, which is the basic measuring element of tillage operation, was measured using RTK–GPS (Span CPT, NovAtel Inc., Calgary, Canada) and an antenna attached to the tractor's center of gravity. In addition, the RTK base station was installed to ensure stable RTK–GPS status. The precisely measured traveling speed with RTK–GPS was used as a factor to determine the longitudinal slip ratio, which is the basic factor for evaluating the working performance of a tractor. The detailed lateral error measurement system configuration is shown in Figure 1.

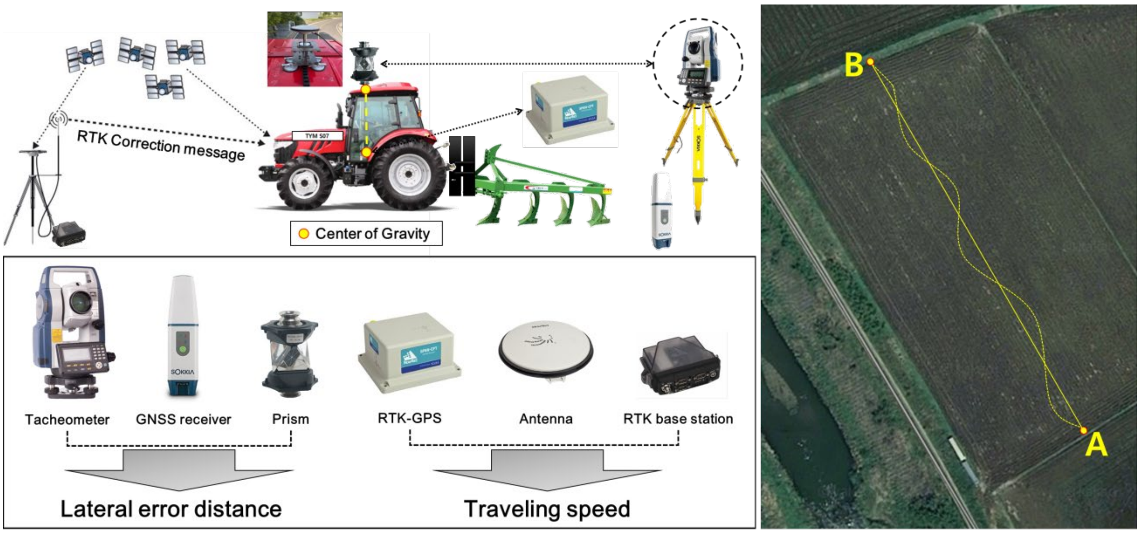

Figure 1. Configuration of lateral error distance system.

2.3 Load measurement system

The load measurement system was configured to measure the draft force and wheel torque off agricultural tractor. The detailed configuration of load measurement system is shown in Figure 2. In this experiment, the torque meter (PCM16, MANNER, Spaichingen, Germany) and the telemetric proximity sensor (PRDCML30–25DN, Autonics, Busan, Korea) were used to measure both the torque and the rotational speed of the agricultural tractor. The torque meter was installed on each of the four axle shafts. One antenna was provided for each torque meter. The axle torque data measured at the torque meter were amplified by the amplifier in the torque meter and transmitted to the antenna, and the data transmitted to the antenna were transmitted to the meter along the cable line. The nominal load of the torque meter was 20 kNm, the maximum load was 400%, and the sensor was of a strain gage type. The sampling rate was 4 kS/s, the maximum axle rotation speed was 4000 rpm. The operating temperature was -25 to 125 ℃. The 6–component load cell (UU–T2, DACELL, Cheongju, Korea) was installed between the moldboard plow and tractor body rear side for measuring draft force. The 6-component load cell consisted of three load cells measuring the horizontal force and three load cells measuring the vertical force. In this experiment, only three load cells were used to measure the horizontal component of the implement draft.

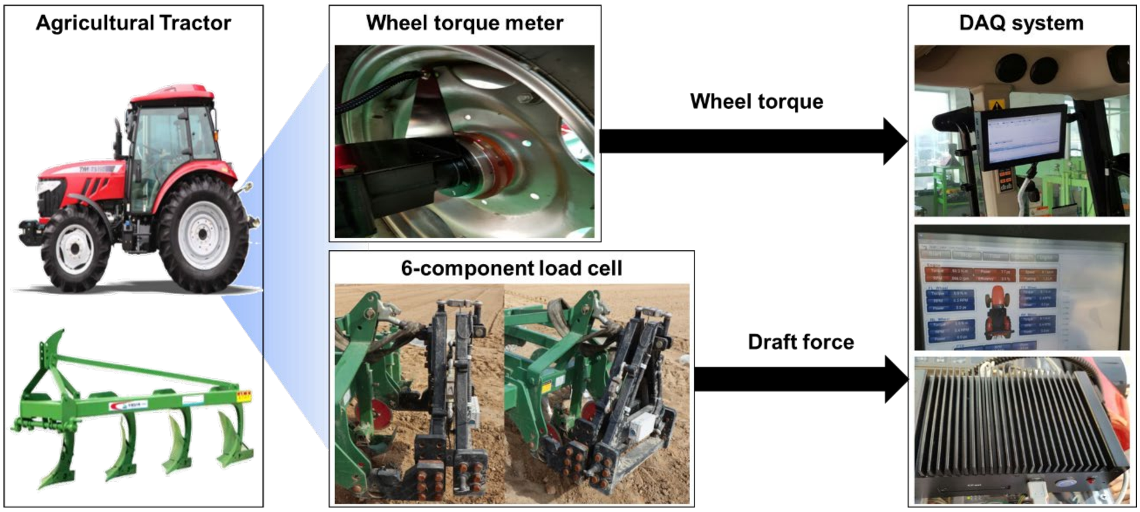

Figure 2. Configuration of load measurement system.

2.4 Measurement of soil physical properties

Tractor tillage operations have a major impact on crop growth and crop yields. The plow layer is the target tillage depth section that is cultivated annually or periodically through an agricultural tractor. The thickness of the plow layer is usually 5–25 cm, and this layer is often greatly worked on in relation to tillage operation, fertilizer, irrigation, and crops. The physical properties of soil such as the cone index, moisture content, and soil classification affect the interactions between the soils and the agricultural machine. The measurement process of soil properties is shown in Figure 3. In order to analyze the lateral error distance of autonomous tractor according to work load during tillage operation, the soil physical properties (cone index, moisture content, and soil classification) of the test site were confirmed using a cone penetrometer (FieldScout SC 900, Spectrum Technologies, Aurora, USA) and a soil sensor (FieldScout TDR 350, Spectrum Technologies, Aurora, USA). The measured soil properties such as cone index (CI), the moisture content (MC), and soil classification by particle size were analyzed following USDA standard methods.

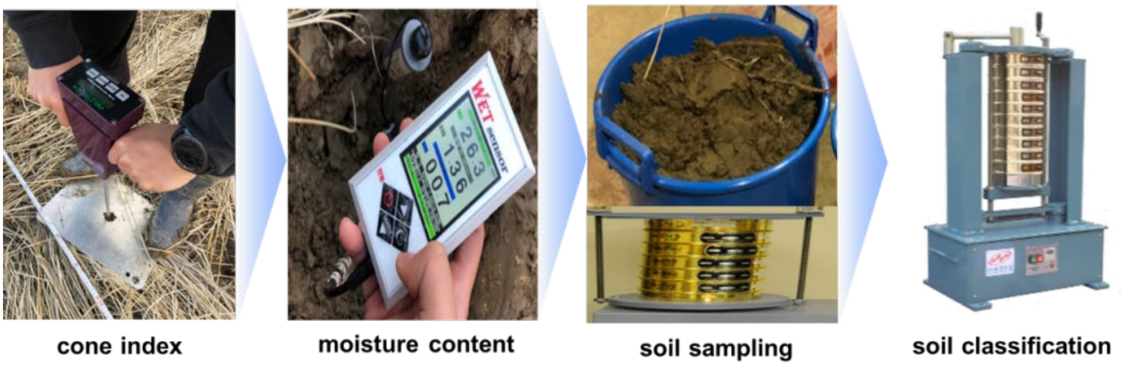

Figure 3. Test procedure of soil physical properties measurement.

2.5 Test procedure

The field experiments were conducted in Kumam–ri, Songsan–myeon, Chungcheongnam–do, Korea. The test site is 100×100 (m) in size and is located at latitude and longitude coordinates 36°55’48” N and 126°37’59” E, respectively. The field test was conducted in four–wheel mode and at three gear stages (M2-high, M3-Low, M3-High), which are commonly used to perform moldboard plow operation. The moldboard plow operation was carried out at the lowest tractor 3-point hitch to perform the under top hardpan section of the plow layer.

3. RESULTS AND DISCUSSION

3.1 Soil physical properties

The main analysis results of soil properties are as follows. The average moisture content of the test site was 38.6%, the mean CI was 2407 kPa, and the mean formation depth of hardpan was 12.5-25 cm. A soil particle size analysis revealed loamy sand in all soil layers. High cone index values indicate high soil compaction, which is a major problem when managing poorly drained soils. A soil hardpan layer with high soil compaction resulting from excessive and improper use of agricultural machinery leads to lower soil porosity and air permeability interferes with the growth of crop roots, and poor drainage. Therefore, during moldboard plow operation, the minimum tillage depth should be where soil compaction is increased. Thus, tillage operations should promote crop growth and ensure porosity and air permeability. In general, the results of plow tillage tend to show irregular tillage depths. Based on an analysis of the test results of the cone index, there is a point at a certain depth where an instantaneous slope occurs. The occurrence of an instantaneous slope implies that a rigid plate is located, and this depth is called the top hardpan. Owing to this reason, the target tillage depth must be set considering the hardpan layer, which indicates the distance from the depth of the top hardpan to the depth of the peak cone index. The cone index was measured using a cone penetrometer and detailed analysis results are shown in Figure 4.

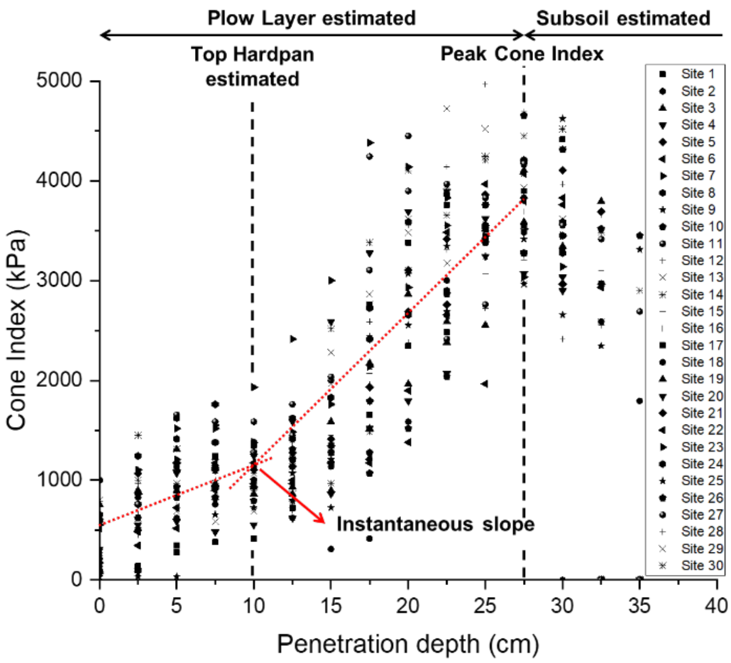

Figure 4. Test results of the cone index using a penetrometer.

3.2 Lateral error distance

The average the draft force were 30.39, 32.57, and 32.79 kW at each gear selection. The draft force increased 2.18 kN when gear shift from M2-High to M3-Low, and increased 0.22 kN when gear shift from M3-Low to M3-High. Almost same torque values were shown in M2-High and M3-Low gear selection. The average front wheel torque were 3267.34, 3693.32, and 3852.37 kW at each gear selection. The average front wheel torque increased 65.98 Nm when gear shift from M2-High to M3-Low, and increased 159.05 Nm when gear shift from M3-Low to M3-High. The front axle load showed a tendency to increase as the number of gears selection. The average the rear wheel torque were 6080.12, 6934.53, and 6727.92 Nm at each gear selection. The rear axle load, which is the most affected factor according to the traveling speed of the agricultural tractor, the tillage depth of the attachment workstation, and the operation type, was found to be the largest in M3-Low gear selection, not M3-High. This is judged to have resulted in a relatively large slip rate at the M3-High gear selection, resulting in a torque loss. The overall data tends to be similar to the traveling speed data as the number of gears selection. However, if the draft force values were similar, the lateral error was greatest in the M2-Low gear selection with a large rear wheel torque. Based on these results, the lateral error of the autonomous tractor is judged to be most affected by the rear wheel torque rather than the draft force and front wheel torque. The detailed overall test results of the lateral error distance according to work load are listed in Table 2.

Table 2. Lateral error distance according to draft force and wheel torque.

Gear selection	Tillage depth (cm)			
	Draft force (kN)	Front wheel (Nm)	Rear wheel (Nm)	Lateral error (cm)
M2-High	30.39	3627.34	6080.12	4.59
M3-Low	32.57	3693.32	6934.53	7.21
M3-High	32.79	3852.37	6727.92	5.88

4. CONCLUSION

A lateral error measurement system and load measurement system are proposed here for measuring tractor work load and lateral error distance during moldboard plow operation. This system configuration allows for precise measurement of lateral error distance, which was previously difficult to measure, and shows the effect of work load on path-following performance of autonomous tractor. The conclusions of this study are as follows.

The work load has a great effect on the lateral error distance of autonomous tractor during moldboard plow operation. In particular, the rear axle load was found to have a significant effect on lateral error compared to draft force and front axle load. Therefore, the influence of work load should be considered when analyzing the lateral error distance of autonomous tractor in an actual paddy field.

In conclusion, the effect of work load on the lateral error distance of an autonomous tractor during moldboard plow operation was confirmed with the measurement system configuration presented in this paper. These findings can be used in future research on the path-following performance of autonomous agricultural machinery.

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