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Testing the Tractor Behavior Simulation with Experimental Driving of a Model Tractor

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In this study, we have performed an experimental driving of model tractors, and through a comparative analysis between the result and the results from previously developed behavior simulation programs for the tractors, we have examined the agreement of the simulation program with the real–world situations.

The main results are as below.

1. As the slope became steeper, the results from the experiment show that the pitching angular velocity decreased when climbing over the bump but there was no change in the simulation.
2. As for the lateral slant, the simulation, which unlike the results of the experiment, showed that the pitching angular velocity was smaller when the wheel on the lower side climbed over the bump and that the rolling angular velocity registered similar tendencies, which agrees with the prediction that side rollover occurs more easily when passing an obstacle on the higher side.
3. In the condition in which the two wheels climb over the bump at the same time, the simulation results were similar in all cases, whereas the experimental results showed bigger pitching angular velocity bigger when going uphill.
4. In all experimental conditions, the rolling angular velocity was measured to be bigger when getting off the bump than when getting on it, but the simulation results showed opposite results.

Overall, the simulation results showed similar results as those of the model tractor driving experiment, which proves the usefulness of the simulation. However, if the simulation program developed in this research is improved by further research having more careful consideration of the differences in the results, it would be possible to develop a tractor behavior simulation program that is more suited to the real–world situation.

Key words: model tractor, behavior simulation, slope, pitching, rolling, angular velocity

INTRODUCTION

In the previous study, we have developed a simulation program that comprehends the tractor behaviors by solving the equation of motions, but it was difficult to assert that it closely resembles real–life situations. Therefore, this study aims to examine if the simulation program agrees with the real–life situations by obtaining data from the actual tractor driving experiment and comparing it with the results from the tractor behavior simulation program developed for analytical purpose. However, since there are diverse limitations on the driving experiments with real tractors, we have performed driving experiments with miniaturized model tractors with a front–wheel pivot mechanism.

MATERIALS AND METHOD

Fig. 1 shows the tractor model used in the experiment. Specifications and parameters are shown in Table 1 and Table 2, respectively.

First of all, to determine the spring constant k and the viscous damping coefficient c, we performed the preliminary experiment three times in going over the bump with a height of 10 mm and a width of 5 mm that stood 15 cm away from the center of the front wheels. Using a 9–axis wireless accelerometer with a mass of about 35 g, we measured the accelerations in the up–down, forward–backward, and left–right directions and the angular velocities in the pitching, rolling, and yawing directions. And we chose the simulation coefficients that registered a value closest to the measured results as the coefficients for the model tire. As the preliminary experiment showed that when k=1400 (N/m), c=45 (Ns/m), the simulation and the measured values of the acceleration in the up–down direction and the angular velocity in the pitching direction came closest, we decided to use these values for k and c of the model tire.

And the acceleration sensor was installed a little further forward from the center of gravity, considering the space, the installation method, etc. The moment of inertia for the model tractor in the respective directions was calculated by considering both the machine and the operating tools as rectangular parallelepipeds.

The model tractor driving experiment adopted 10 conditions as shown in Table 3, including 3 conditions of 0°, 5°, and 10° for the slope of the road surface in the traveling direction, the 3 conditions of 0°, 5°, and 13° for the slope in the lateral direction, and 2 conditions of 5 mm and 10 mm as the bump height, and considering all possible cases such as only one wheel on either side

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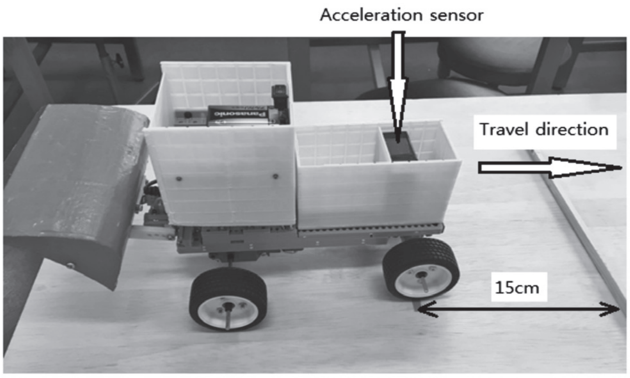

Fig. 1. Model Tractor.

Table 1. The specifications of the model tractor

Entry	Value
Machine's mass (machine + operating tool) (kg)	0.85
Full length (cm)	20
Full width (cm)	8
Overall height (cm)	12
Wheelbase (cm)	14.35
Front wheel track (cm)	10.5
Rear wheel track (cm)	13.6
Horizontal distance from the center of gravity of the machine to front wheel (cm)	13.1
Vertical distance from the center of gravity the machine to road surface (cm)	4.2
Tire diameter (cm)	5.5

Table 2. Model tractor parameters

Entry	Sign	Value
Moment of inertia in the pitching direction (kg/mm^2)	I_y	2083.4
Moment of inertia in the rolling direction (kg/mm^2)	I_x	1639.1
Lateral distance from center of gravity to right front wheel(cm)	B_{fr}	5.25
Lateral distance from center of gravity to left front wheel (cm)	B_{fl}	5.25
Lateral distance from center of gravity to right rear wheel (cm)	B_{rr}	7.8
Lateral distance from center of gravity to left rear wheel (cm)	B_{rl}	7.8
Distance from center of gravity to front wheel (cm)	L_f	13.1
Distance from center of gravity to rear wheel (cm)	L_r	6.87
Height of center of gravity (cm)	L_g	4.2
Machine's mass (kg)	M	0.85

going over the bump or both wheels going over the bump.

Considering the real–life situations we made a difference in the shape of the bump by having the tractor pass a square bump with a height of 5 mm and a width of 5 mm at 15 cm away from the center of gravity of the machine's front wheels when only one tire on either side is going over the bump or having the bump with the same width but with a double height of 10 mm when the tires on both sides go are going over the bump simultaneously.

We performed the driving experiment three times, respectively, for each case, and measured the acceleration in the up–down, left–right, and forward–backward directions and the angular velocity in the respective directions of pitching, yawing, and rolling using the accelerometer. And we set the machine speed to be 0.2538 m/s, which is derived from average time taken for the model to travel 30 cm of level road.

Table 3. Experiment conditions

Condition	Uphill slope (°)	Lateral slope (°)	Wheel going over the bump	Bump height (mm)
1	0	0	Both wheels	10
2	0	0	Left wheel	5
3	5	0	Left wheel	5
4	10	0	Left wheel	5
5	0	5	Wheel on lower side	5
6	0	5	Wheel on higher side	5
7	0	13	Wheel on lower side	5
8	0	13	Wheel on higher side	5
9	5	0	Both wheels	10
10	0	5	Both wheels	10

RESULTS AND DISCUSSION

Driving Experiment

Under the different conditions, the measured angular velocities for the machine's pitching, yawing, and rolling were shown in Fig. 2. The change in the machine's rolling angle is very small during when only one front wheel of the model tractor is passing over the bump due to the front–wheel pivot mechanism on the model tractor.

In conditions 2, 3, and 4 only the slope in the traveling direction is varied from 0° to 5° and 10°, while keeping all the other conditions as unchanged. The figure shows that in for conditions 2 and 3, the peak value of the pitching angular velocity (hereafter, each maximum value represents an absolute value) was about 1 rad/s, whereas in for condition 4, it was about 0.6 rad/s, with the pitching angular velocity rather decreasing as the uphill slope increased. The reason for this can be thought as the insensitive transmission of the ground reaction force of the front–axle onto the machine due to the load transferred to the rear–axle as the slope of the uphill increases, but we think that the major cause comes from the fact that the model tractor travels slower on an uphill than on a level road. We believe that this needs to be checked with a makeup experiment having a big enough model driving force. The yawing angular velocity was approximately 0.7 rad/s and the rolling angular velocity was approximately 1.4 rad/s, and they did not show significant changes for different conditions.

Indeed, we observed that the peak value of the pitching angular velocity did not show a significant change, as expected, for conditions 5, 6, 7, and 8 for travelling on a laterally sloped roads, but in contrary to our expectations, the rolling angular velocity where measured to be higher for conditions 5 and 7, in which the vehicle passes over the bump on the lower side, that for conditions 6 and 8, in which it passes over the bump on the higher side. We understand that this is due to interference of the pitching motion with bigger yawing and slippage that occur when passing over the bump on the higher side.

When both wheels are going over the bump simultaneously, the pitching angular velocity increases while the front wheels are climbing over the bump, as the slope of the uphill increases, as demonstrated in the conditions 9 and 10. We believe that this is due to a load transfer, in which smaller load is applied on the machine's front

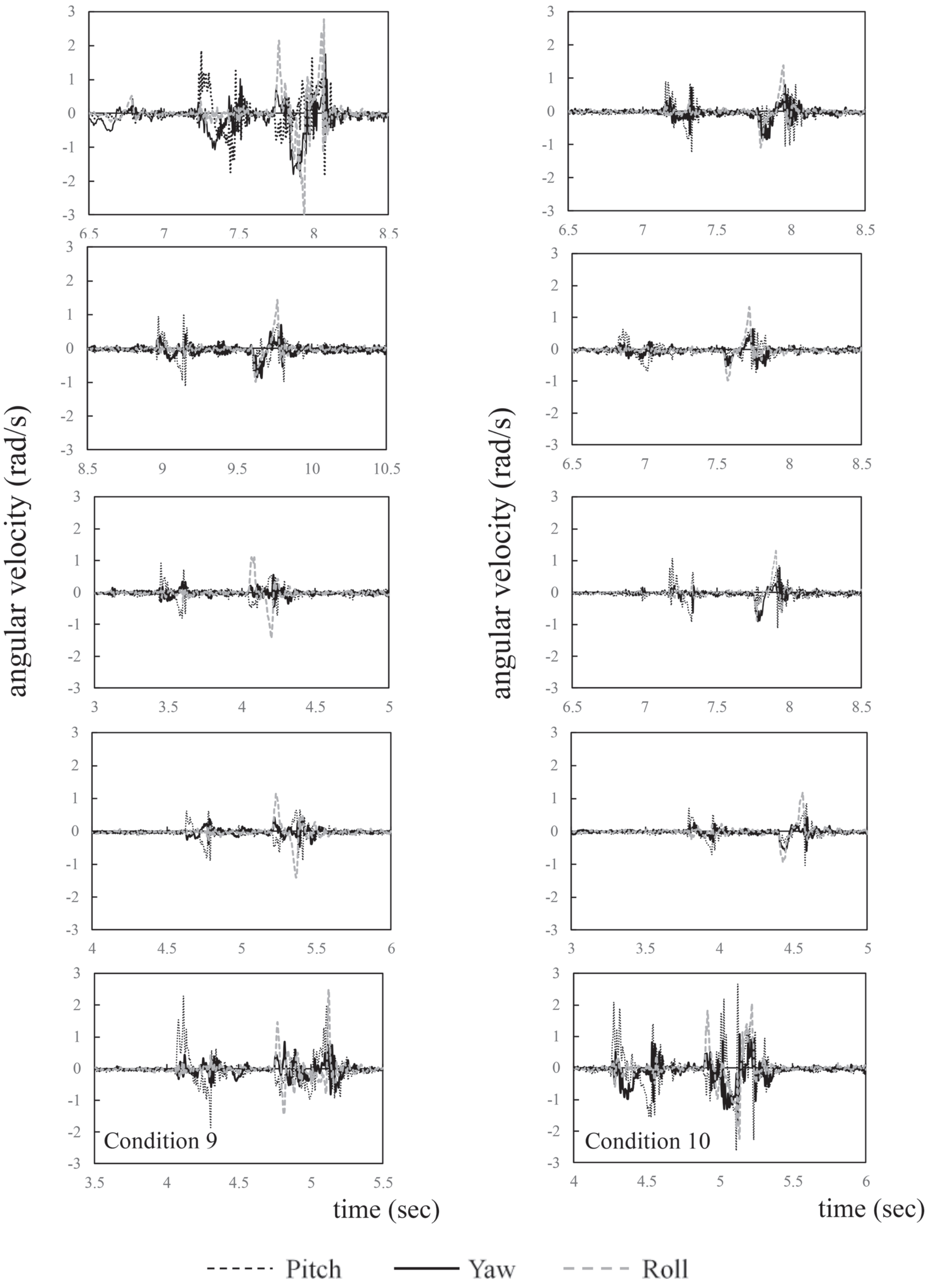

Fig. 2. Angular velocity change under different conditions.

wheels as the slope becomes steeper, and therefore, the front wheels get lifted more abruptly while climbing up the bump.

When the tractor climbs the bump on an uphill road or in a sloped area, bigger angular velocity causes the occurrence of rollover to be more likely, thus creating an accident–prone situation. If yawing motion does not occur when a tractor actually drives, it is easier for rollover to occur when its front wheels go over the bump in an uphill sloped area or the wheel on the higher side goes over the bump. In this experiment, results that are partly contrary to our expectation were derived because the yawing and slippage motions occurred. This suggests that the yawing and slippage motions may significantly affect the safety of the tractor behavior during the tractor driving, so they should also be sufficiently considered in the following studies on tractor safety.

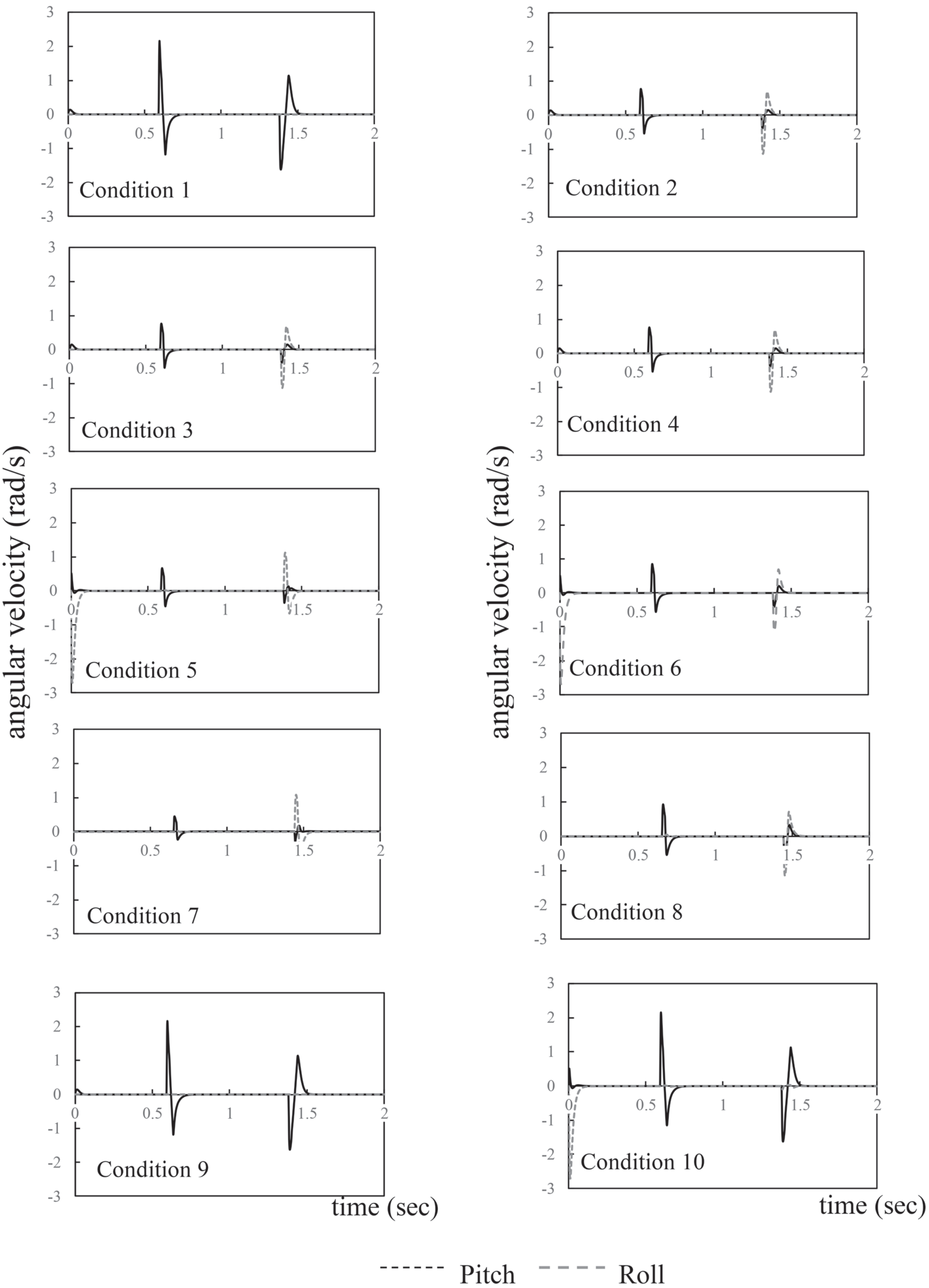

Fig. 3. The results of the pitching and rolling angular velocity simulation.

Comparison between the simulation and the experiment

By analytically comparing the results of the tractor behavior simulation, developed in our earlier study and the measurements performed in this study with the model tractor, we tested the usefulness of the developed simulation model.

The simulation, for which the same values as the specifications and parameters of the model tractor were entered, was performed under the same 10 conditions as with the driving experiment.

Fig. 3 shows the results of the pitching and rolling angular velocity simulation under the 10 conditions.

The results of the experiment showed that as the slope of te uphill became steeper, the pitching angular velocity decreased when climbing over the bump, whereas the simulation showed no changes. This may have been caused due to the difference in conditions, where the machine speed being constant regardless of the angle of the slope in the simulation, whereas the machine speed decreases in the driving experiment.

For conditions of 5, 6, 7, and 8 with lateral slope, the pitching angular velocity was smaller in the conditions of 5 and 7, in which the vehicle climbs over bump with the wheels on the lower side than in the conditions of 6 and 8 in which the vehicle climbs over the bump on the higher side, and the rolling angular velocity, despite no significant difference, showed the similar pattern as the pitching angular velocity, which matches with our expectation that a lateral rollover would more likely to occur when passing an obstacle on the higher side. Under the condition in which both wheels climb over the bump simultaneously, the simulation showed similar results in all cases, whereas the experiment showed bigger pitching angular velocity under condition 9, in which the vehicle was supposed to travel uphill, thus showing that the simulation failed to reflect it properly. In the experiment, the rolling angular velocity was measured to be bigger in all the conditions when the wheel came down the bump than when it climbed up the bump, whereas the simulation showed the opposite results. We believe that that is due to the yawing motion and slippage that occurs in the experiment, which has not been considered in the simulation.

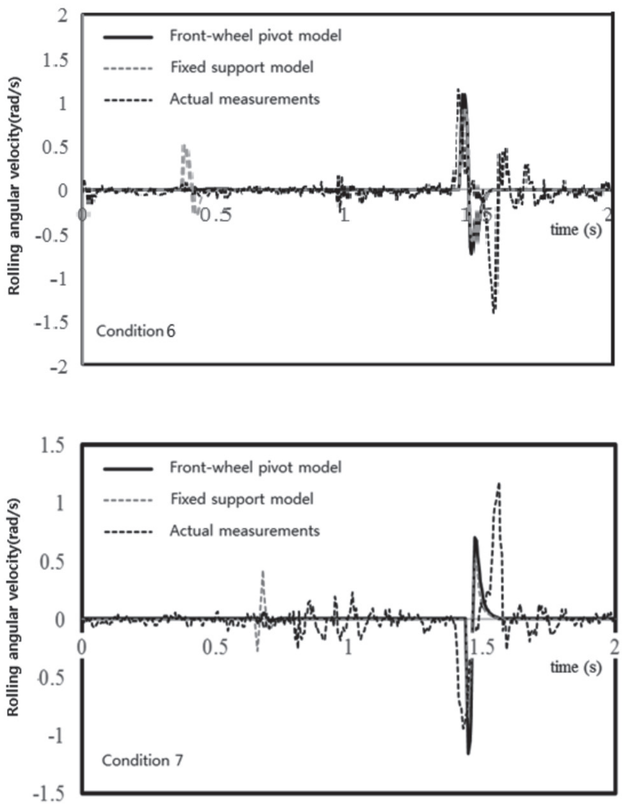

Fig. 4. Comparison between the rolling angular velocity values in the experiment and the simulation results (Condition 6 and Condition 7).

Fig. 4 shows the comparison between the rolling angular velocity values in the experiment and the simulation results, as an example, of conditions 6 and 7.

In condition 6, in which the wheel on the lower side climbs over the bump, the front wheel climbs over the bump at approximately 0.4 s and the rear wheel climbs over the bump at approximately 1.5 s. When the front wheel passes over the bump, a displacement in the rolling angular velocity is observed in the fixed support model, whereas no displacement is observed in the front–wheel pivot model and actual measurements. In addition, when the rear wheels pass over the bump, the front–wheel pivot model shows values very close to the actual measurements. In condition 7, in which the wheel on the higher side passes over the bump, similar tendencies can be observed. This shows that the simulation program excellently reflects the benefits of adopting the front–wheel pivot mechanism.

CONCLUSION

This study performed a model tractor driving experiment, and by analytically comparing its results and those of the tractor behavior simulation program developed in an earlier study, we examined if the simulation program matched with real–life situations.

The key results are as follows.

1. As the slope became steeper, the results from the experiment show that the pitching angular velocity decreased when climbing over the bump but there was no change in the simulation.
2. As for the lateral slant, the simulation, which unlike the results of the experiment, showed that the pitching angular velocity was smaller when the wheel on the lower side climbed over the bump and that the rolling angular velocity registered similar tendencies, which agrees with the prediction that side rollover occurs more easily when passing an obstacle on the higher side.
3. In the condition in which the two wheels climb over the bump at the same time, the simulation results were similar in all cases, whereas the experimental results showed bigger pitching angular velocity bigger when going uphill.
4. In all experimental conditions, the rolling angular velocity was measured to be bigger when getting off

the bump than when getting on it, but the simulation results showed opposite results.

Overall, the simulation and the model tractor driving experiment showed similar results, proving its usefulness, but they showed the differences as summarized above. The causes of the differences would be as follows: First, the tractor speed remains the same in the simulation whereas the tractor slows down when encountering an uphill road or an obstacle in actual driving. Second, in an actual driving situations, the yawing motion and the slippage occurred, which were failed to be considered for the simulation. Third, for spring constant and viscous damping coefficient, predicted values were used instead of actual measurement values. Fourth, acceleration sensor were failed to be installed at the center of gravity of the machine. Fifth, other errors may have been caused in the driving test which used a model tractor instead of a real tractor.

If follow–up studies pay more attention to these issues and thereby improve the simulation program that this study has developed, it will be able to develop a tractor behavior simulation program that comes closer to real–life situations.

AUTHOR CONTRIBUTIONS

J. Choe designed the study, analyzed the data and wrote the paper. H. Akimune and S. Shine performed the scale model experiments. T. Okayasu and Y. Hirai participated in the design of the study and performed the experiments. E. Inoue and M. Mitsuoka designed the study, supervised the work, wrote the paper and provided facilities and resources. All authors assisted in editing of the manuscript and approved the final version.

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