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Slippage Performance of an Agricultural Unmanned Ground Vehicle Equipped With Tracked Locomotion Platform

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ABSTRACT

Slippage performance of an unmanned ground vehicle with tracked locomotion platform for autonomous transportation of agricultural payloads in greenhouse constructions leads to appearance of an applied research in this study. This novel aim has been chosen based on operational requirement of the vehicle. To this aim, various payloads mounted on a trailer (1-5 kN) were pulled by the vehicle through diverse drive speeds (0.17-0.5 m/s). Results illuminate that vehicle drive speed and payload weight had consequential contribution to the slippage. Linear regression approximations demonstrate that dual cumulative contributory effect of the drive speed and payload weight on the slippage (0.64-18.30 %) was increasingly synergetic. Overall, numerical and analytical descriptions of the results as well as practical suggestions provide appropriate guidelines for optimization of slippage performance of the vehicle working in greenhouse constructions.

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INTRODUCTION

Mobile robots have successfully carried out specialized operations in various environments, including indoor and outdoor conditions such as underwater, air, and ground surfaces. The mobile robots are employed for the operations in order to eliminate human intervention in hazardous environments and increase operation efficiency (Bechar & Vigneault, 2016).

Unmanned ground vehicles are a group of mobile robots (Ghaffari et al., 2004; Zhang et al., 2014) which are operating in contact with ground. This type of vehicles is remotely controlled without presence of an onboard human (Zeng et al., 2022). A vehicle supervisor can control vehicle behavior from an outside position of working environment using a human-machine interface (Man et al., 2018).

As main purposes of employment of unmanned ground vehicles are complete elimination of human in laborious and repetitious tasks, and exposition of human to harmful environments (Ni & Xiang, 2021), the vehicles have increasingly employed for various tasks in forest (Pierzchala et al., 2018; Ribeiro et al., 2017), industry (Christie et al., 2017; Lazna et al., 2018; Peterson et al., 2019), construction site (Asadi et al., 2020; Castaman et al., 2021), urban road (Yang et al., 2021), livestock (Meena & Agilandeeswari, 2021) and agriculture (Bonadies & Gadsden, 2019; Mammarella et al., 2022; Nieminen & Sampo, 1993).

One of specific application of unmanned ground vehicles in agriculture is tractor vehicles which transport agricultural payloads through pulling of a following trailer. This type of the vehicles can be used for capacity augmentation of autonomous transportation of product bin in orchard and farm (Bayar et al., 2015; Guevara et al., 2020; Kayacan et al., 2014; Kayacan et al., 2016; Kayacan et al., 2018) or spray tank in greenhouse constructions (Singh et al., 2005).

In this realm, robotic contractor companies encourage farmers and associated experts to employ unmanned tracked vehicle rather than unmanned wheeled vehicle. This encouragement is raised based on two agricultural advantages of tracked running gear system than other ones (wheeled, and hybrid (combination of tracked and wheeled)) which are usually employed in unmanned ground vehicles (Kamel et al., 2020).

The first advantage is related to soil compaction. As contact area between the tracked system and ground surface is higher than that of the wheeled system (Bashford et al., 1988; Esch et al., 1990; Khan et al., 2021; Lamande et al., 2018; Mudarisov et al., 2020; Okello et al., 1994; Oljaca, 1994; Wong & Huang, 2006), soil compaction caused by the tracked system is lower than that of the wheeled system with the same vehicle weight (Ansorge & Godwin, 2008; Brown et al., 1992; Burger et al., 1985; Bygden et al., 2004; Chi et al., 1993; Golanbari et al., 2025; Keller & Arvidsson, 2016; Keller et al., 2002; Murosky & Hassan, 1991). According to findings of many researches (Al-Adawi & Reeder, 1996; Burt, 1993; Galambosova et al., 2017; Gameda et al., 1985; Gaultney et al., 1982; Hakansson, 1994; Hakansson & Reeder, 1994; Hakansson et al., 1988; Hassan et al., 2007; Ishaq et al., 2001; Kulkarni et al., 2010; Lavoie et al., 1991; McKyes et al., 1980; Mileusnic et al., 2022 Mulazzani et al., 2022; Nawaz et al., 2013; Ngunjiri & Siemens, 1995; Ohu et al., 1985; Patel et al., 2020; Raper, 2005; Shaheb et al., 2021; Sidhu & Duiker, 2006; Voorhees, 1986; Voorhees, 1991; Wolf & Hadas, 1984), soil compaction noticeably reduces crop yield.

The second advantage is related to power loss caused by slippage of driving running gear. Many researches (Arvidsson et al., 2011; Bashford & Kocher, 1999; Brixius & Zoz, 1976; Culshaw, 1988; Domier et al., 1971; Dwyer et al., 1993; Molari et al., 2012; Osborne, 1971; Rasool & Raheman, 2018; Sutoh et al., 2012; Taylor & Burt, 1975; Turner, 1995; Wakabayashi et al., 2009) have indicated that slippage as well as associated power loss of driving running gear of the tracked system is lower than that of the wheeled system for generation of the same drawbar pull with the same vehicle weight. Hence, unmanned tracked vehicle can be performed with lower internal power source than that of unmanned wheeled vehicle in the same working conditions. This fact enhances working efficiency of autonomous operations.

According to the two abovementioned advantages, farmers and associated experts prefer to employ unmanned tracked vehicle rather than unmanned wheeled vehicle. Howbeit, one concern for application of unmanned tracked vehicle has been frequently reported by them. This concern is focused on insufficient power for pulling of a following trailer with overweight of agricultural payloads (such as chemical materials in spray tank or collected product in the bin). In this state, the vehicle mobility is decreased by excessive slippage of the vehicle tracks. This challenging problem results in power inefficiency of the vehicle for pulling of the trailer.

To obviate the challenging problem, the vehicle supervisor changes drive speed or payload weight, or both of them, in a random manner for reduction of the slippage. These actions with no previous information might be instantaneously effective, but they are not perpetually helpful for the challenging problem. Since, impetus for present applied research has been come from this problematic challenge. Therefore, research aim reflected in present paper has been oriented towards elucidation of slippage performance of the vehicle during straightforward pulling of the trailer with diverse payload weights and drive speeds. It is expected that numerical and analytical descriptions of the research results shed light into knowledge of phenomena as well as provide appropriate guidelines for the challenging problem.

To conduct the research, in the first stage, preceding attempts documented by researchers have been reviewed and analyzed in case of unmanned tracked vehicle. It has been found that publicly available literature provides suitable information for various aspects of the vehicles. This information is useful for guidance control system (Cho & Ki, 1996), mission battery storage capacity (Sadrpour et al., 2013), instability (Babu et al., 2018), dynamic modeling (Zou et al., 2018), thrust force (Shin et al., 2020), path tracking (Guo et al., 2022) and power characteristics (Shafaei & Mousazadeh, 2023).

In the first stage of the research, preceding attempts documented by researchers (Badgujar et al., 2022; He et al., 2022; Herzog et al., 2007; Jiao et al., 2023; Li et al., 2023; Li et al., 2021; Wang et al., 2016; Wang et al., 2018; Xu et al., 2022) have been reviewed and analyzed for slippage performance of unmanned tracked vehicles. Although the attempts have tried to present practical suggestions for the slippage, there is no similar report for the challenging problem raised in current research.

From the literature review outlined above, it is clear that there is no information about slippage performance of the vehicle in agricultural pulling tasks. Hence, it can be claimed that new research aspect of the vehicle has been emerged in this study in order to solve the challenging problem and enrich state of the art. Thus, novel contribution of the research aim is highlight.

In the second stage of the research, necessary theoretical and experimental works have been accomplished (Section 2). Analysis of numerical results obtained from the works has been performed in the third stage (Section 3). Meanwhile, the fourth stage concludes the results and provides appropriate guidelines for vehicle supervisor (Section 4).

MATERIALS AND METHODS

Experimental Setup

In this study, an unmanned tracked vehicle was used. Two hydraulic motors were responsible of motion power provision for tracked running gear system of the vehicle. A hydraulic unit at base station supplied hydraulic power of the motors. The vehicle was remotely controlled by vehicle supervisor from a distance using manual control joystick (teleoperation) (Fong & Thorpe, 2001; Hokayem & Spong, 2006; Ju & Son, 2019; Moniruzzaman et al., 2022; Nguyen & Ryu, 2012; Passenberg et al., 2010; Sheridan, 1995; Slawinski et al., 2007). Table 1 summarizes technological parameters of the vehicle.

Table 1. Technological parameters of the unmanned tracked vehicle

Parameter	Value	Unit
Total weight	2167.27	N
Drawbar height	0.27	m
Height	0.52	m
Width	0.90	m
Length	1.20	m

Longitudinal slippage of the tracked running gear system of the vehicle was measured through comparison of ground speed of powered tracks with that of auxiliary non-powered rigid wheel. Based on this method, three 500-pulse encoder transducers (model: E50S8-500-6-L-5, country: Korea, manufactory: Autonics) were coupled with center point of the two tracks and the rigid wheel (Gonzalez & Iagnemma, 2018; Pranav et al., 2010; Teji et al., 2023). The outfitted vehicle is displayed in figure 1. Data released by the transducers were collected by a control unit of the vehicle at the base station. This collection process has been accomplished with frequency of 30 Hz. Moreover, the control unit continuously computed and stored values of the slippage of the vehicle tracks based on equation 1 (Shafaei et al., 2019).

$$LS_t = \left(1 - \left(\frac{\left[\frac{EPN_{aw} \times \pi RD_{aw}}{EPN \times DCT}\right]}{\left[\frac{EPN_{vt} \times \pi H_{vt}}{EPN \times DCT}\right]}\right)\right) \times 100 \qquad (1)$$

Figure 1. The unmanned tracked vehicle outfitted with three encoder transducers (right and left driving tracks, and auxiliary rigid wheel)

Pulling Trails

Numerous pulling trials were performed in order to study contributory effect of selected causative variables (vehicle drive speed and payload weight) on slippage performance of the unmanned tracked vehicle in agricultural pulling tasks.

The pulling trials were performed based on a standard suggested by Organization for Economic Co-operation and Development. Based on the standard, the pulling trials were completed on concrete flat surface in order to exclude contributory effect of various conditions of ground surface on obtained data. Nebraska Tractor Test Laboratory has also employed the standard for drawbar pull appraisal of tractors (Howard et al., 2013; Kocher et al., 2011; Kocher et al., 2017; Roeber et al., 2017).

The pulling trails were performed with steady state conditions in direct motion (10 m) of the vehicle. It was ensured that the vehicle and trailer were kept to the flat surface in parallel manner. It should be mentioned that the surface was flat in both directions (lateral and longitudinal directions) (Bai et al., 2020; Upadhyaya et al., 2001). Levels of the causative variables were set as 0.17, 0.33 and 0.5 m/s, and 1, 2, 3, 4 and 5 kN for the drive speed and payload weight, respectively. For each combination of the levels, the trail was repeated three times. Overall, 45 trails were completed for collection of the slippage data. Meanwhile, magnitude of payload weight was set based on total weight of the trailer and its additional payloads.

Statistical calculations

Variations of data obtained for the slippage of the unmanned tracked vehicle in agricultural pulling tasks were studied by means of some statistical indicators (mean, standard deviation, coefficient of variation, and coefficient of non-uniformity). Following equations 2-5 present the indicators (Shafaei & Kamgar, 2017).

$$M = \frac{\sum_{i=1}^{i=N} VS_i}{N} \quad (2)$$

$$SD = \frac{\sqrt{\sum_{i=1}^{i=N} (VS_i - M)^2}}{N} \quad (3)$$

$$CV = (\frac{SD}{M}) \times 100 \quad (4)$$

$$CNU = (\frac{VS_{max} - VS_{min}}{M}) \times 100 \quad (5)$$

Appraisal of significant contributory effects of the causative variables and their dual cumulative contributory effects on the slippage of the vehic\le was carried out by analysis of variance method. The method was developed based on 99 % probability level and factorial randomized design. Results of analysis of variance were used to calculate contribution percentage of the variables to the slippage on the basis of equation 6 (Shafaei & Kamgar, 2017). Additionally, significant difference between levels of the variable was apprised using Duncan's test at 99 % probability level.

$$PC_{cv} = \frac{SSV}{TSS} \times 100 \quad (6)$$

Regression Approximation of the Slippage

Mathematical approximation of contributory effect of the causative variables on the slippage of the unmanned tracked vehicle in agricultural pulling tasks ascertains physics of phenomenon. Multiple linear regression is one of outperforming mathematical approximations, because of easy interpretation and simple application. Hence, the regression approximation (equation 7) (Shafaei & Kamgar, 2017) was fitted to actual data of the slippage. According to results of analysis of variance in previous subsection, if each variable was consequential, it was included in the regression. Finally, coefficients and constants of the fitted regressions were determined.

$$VS = a_0 + \sum_{i=1}^{i=N} (a_i \times CV_i) \quad (7)$$

Fitness accuracy of the regressions was apprised by some indicators known as coefficient of determination, root mean square error, mean relative deviation modulus and, mean of absolute values of regression errors. Equations 8-11 express the indicators (Shafaei et al., 2019; Shafaei et al., 2016).

$$R^2 = 1 - \frac{\sum_{i=1}^{i=N} (VS_{acti} - VS_{apri})^2}{\sum_{i=1}^{i=N} (VS_{acti} - VS_{aprave})^2} \quad (8)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{i=N} (VS_{apri} - VS_{acti})^2} \quad (9)$$

$$MRDM = \frac{100}{N} \sum_{i=1}^{i=N} \left(\frac{|VS_{apri} - VS_{acti}|}{VS_{acti}} \right) \quad (10)$$

$$MAVRE = \frac{1}{N} \sum_{i=1}^{i=N} |VS_{apri} - VS_{acti}| \quad (11)$$

RESULTS AND DISCUSSION

Statistical Reports

Table 2 groups statistical indicators calculated for the slippage of the unmanned tracked vehicle in agricultural pulling tasks. Maximum value of the slippage (18.30 %) in the Table 2 was found for the highest level of payload weight (5 kN) and vehicle drive speed (0.5 m/s). Meanwhile, minimum value of the slippage (0.65 %) in the Table 2 was corresponded to the lowest level of the drive speed (0.17 m/s) and payload weight (1 kN). In the Table 2, low values of standard deviation quantitatively imply reasonable variations of the slippage in the abovementioned ranges. This finding can be also confirmed regarding low values of coefficient of non-uniformity and coefficient of variation listed in the Table 2.

Table 2. Statistical indicators calculated for power efficiencies of the unmanned tracked vehicle

Mean (%)	Standard deviation (%)	Minimum (%)	Maximum (%)	Coefficient of variation (%)	Coefficient of non-uniformity (%)
9.36	6.45	0.65	18.30	68.79	188.37

According to classification of the slippage ranges by previous robotic researchers (Bouguelia et al., 2017; Gonzalez & Iagnemma, 2018; Guo et al., 2020), the mentioned range specifies that the vehicle experienced low slippage (< 30 %) during the pulling trails. Pervious researchers (Yong et al., 1980) has divided track-surface interface into three specific regions of slippage, compaction, and distortion region. Above cutting tip level of the track places between track grousers is distortion region. Particles of soft ground can fill this region. Below tip level of track grouser is compaction region. Particles of soft ground can downwardly displace in this region (sinkage). A very thin layer at tip level of track grouser is slippage region. In slippage region, the slippage of the track occurs. Accordingly, it can be undoubtedly pointed out that the slippage occurred in the slippage region.

Results of analysis of variance for the slippage are reported in Table 3. According to the Table 3, contribution of payload weight and the drive speed to the slippage was consequential at 99 % probability level. Based on this result, the regression approximation of the slippage must be fed with two input variables (payload weight and the drive speed). Similar to this result, previous researchers (Lee et al., 2015; Shafaei & Mousazadeh, 2022) have reported consequential contribution of payload weight and the drive speed to the slippage of unmanned wheeled vehicles during free motion without following trailer.

Figure 2 charts contribution percentage of the causative variables to the slippage. According to the figure 2, the contribution of payload weight was notably higher (32.36 times) than that of the drive speed. Hence, it can be predictable that the contributory effect of payload weight on the slippage was notably higher than that of the drive speed.

Table 3. Results of analysis of variance for motion power efficiency of the unmanned tracked vehicle

Source of variation	Degree of freedom	Sum of squares	Mean square	F value
Drive speed (DS)	2	52.204	26.102	74.628*
Payload weight (PW)	4	1687.132	421.783	1205.909*
DS×PW	8	5.408	0.676	1.933
Error	30	10.493	0.350	-
Total	44	1755.237	-	-

*Significant at $P<0.01$

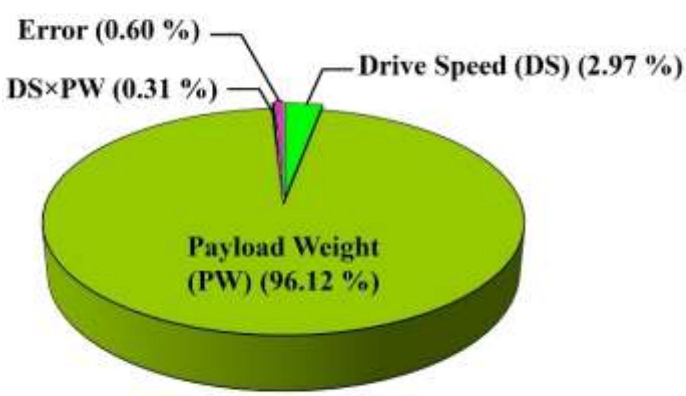

Figure 2. Contribution percentage of causative variables to the slippage of the unmanned tracked vehicle

Contributory effect of vehicle drive speed on the slippage

According to the Duncan's test results, contributory effect of vehicle drive speed on the slippage of the unmanned tracked vehicle in agricultural pulling tasks has been drawn in Figure 3. The Figure 3 portrays when the drive speed augmented from 0.17 to 0.5 m/s, the slippage increased (32.71 %). Direct dependency of motion resistance of tracked running gear system of the vehicle on the slippage is reason for this observation (Kim & Shin, 1985; Onafeko, 1969; Shmulevich et al., 1998; Sitkei, 1966; Suvinen & Saarilahti, 2006; Williams et al., 2019; Ydrefors et al., 2021). When the drive speed increases, internal motion resistance of tracked running gear system increases. Reason for this finding is related to increasing contributory effect of the drive speed on friction of road and idler wheels, and bearings of driving sprocket, and bending resistance and viscoelastic properties of the rubber of the tracked running gear system (Cholodowski et al., 2021; Dudzinski & Cholodowski, 2021; Zhu et al., 2023). Finally, as motion resistance increases, the slippage increases, too.

As the slippage is dictated by magnitude of motion resistance, decrement of motion resistance of tracked running gear system is an effective manner for decrement of the slippage. This can be achieved by tighter tracks. The tighter tracks (initial tension of the tracks must be increased) increase and decrease internal and external motion resistance of the running gear system, respectively (Wong & Preston-Thomas, 1986; Wong & Preston-Thomas, 1988; Wong & Gao, 1994). This results in increment or decrement of total motion resistance regarding ground surface conditions (hard and soft). It is worthwhile to point out that internal motion resistance of metal tracks of the running gear system is higher than that of rubber tracks of the running gear system (Molin & Leviticus, 1995).

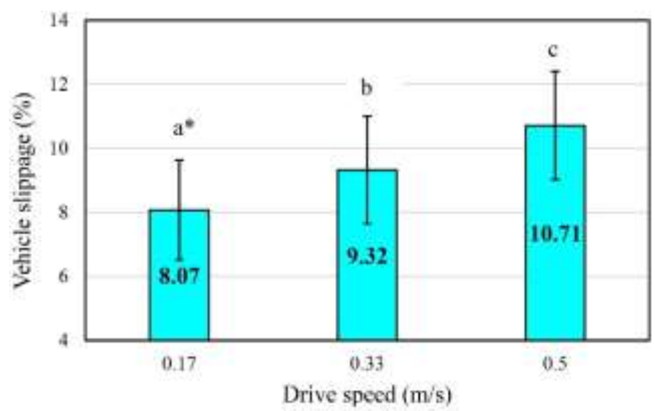

Figure 3. Contributory effect of drive speed on the slippage of the unmanned tracked vehicle

Contributory Effect of Payload Weight on the Slippage

According to the Duncan's test results, contributory effect of payload weight on the slippage of the unmanned tracked vehicle in agricultural pulling tasks has been graphically illustrated in Figure 4. The Figure 4 portrays when payload weight augmented from 1 to 5 kN, the slippage augmented (1240.08 %). Drawbar pull requirement of the vehicle for pulling of payload augments, when payload weight augments, and consequently, the slippage augments regarding drawbar pull-slippage relation. According to the relation, higher slippage of the vehicle tracks is required for higher generation of the vehicle drawbar pull (Book & Goering, 2000; Brusentsev, 1967; Hetherington, 2005; Muro, 1989; Nicolini et al., 2019; Turnage, 1975; Turner, 1984; Wong, 1984; Wong, 1992; Wong, 2009; Wong et al., 2018).

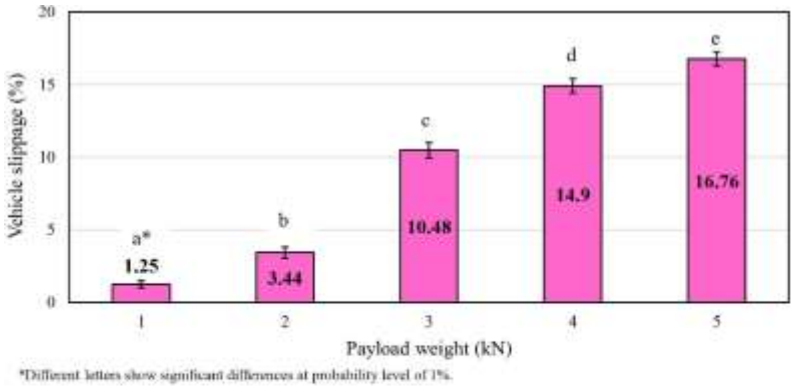

Figure 4. Contributory effect of payload weight on the slippage of the unmanned tracked vehicle

Comparison of contribution of causative variables to the slippage

Comparison of contribution of causative variables to the slippage of the unmanned tracked vehicle in agricultural pulling tasks has demonstrated that the positive contribution of payload weight to the slippage prevailed (37.91 times) than that of vehicle drive speed. These results verify predictions outlined by contribution percentage of the causative variables to the slippage in the Section 3. 1. Therefore, an adjustment of payload weight is recommended as the first priority for optimization of slippage performance of the vehicle in agricultural pulling tasks. It should be pointed out that results of the regression approximations documented in following subset can be undoubtedly advantageous for this optimization. Moreover, the lower slippage can be achieved utilizing slippage control system for the vehicle. Detail description of the control system falls outside of scope of this research and has been given in some previous published works (Choi et al., 2007; Gao et al., 2015; Iagnemma & Dubowsky, 2004; Kim & Lee, 2018; Shafaei & Mousazadeh, 2023; Toupet et al., 2020; Wei et al., 2013).

Regression Approximation of the Slippage

Regarding consequential contributory effects of the causative variables (vehicle drive speed and payload weight) on the slippage of the unmanned tracked vehicle in agricultural pulling tasks, two-variable regressions were fitted to actual data of the slippage with help of equation 12. Table 4 groups accuracy indicators, coefficients, and constants of the regression.

$$VS = a_0 + (a_1 \times VDS) + (a_2 \times PW) \quad (12)$$

The Table 4 indicates that the values obtained from the regressions of the slippage were in good correlation with actual values of the slippage, because of acceptable values of coefficient of determination ($R^2 > 0.9$), root mean square error, mean relative deviation modulus, and mean of absolute values of regression errors.

Table 4. Accuracy indicators, coefficients, and constant of the regressions for power efficiencies of the unmanned tracked vehicle

a_0	a_1	a_2	Coefficient of determination	Root mean square error (%)	Mean relative deviation modulus (%)	Mean of absolute values of regression errors (%)
-6.042	7.993	4.247	0.961	1.240	2.164	1.125

Meanwhile, Figure 5 plots relationship between approximated and actual values. In the Figure 5, falling of data points around the 1:1 line indicates superior ability of the regression for approximation of the slippage.

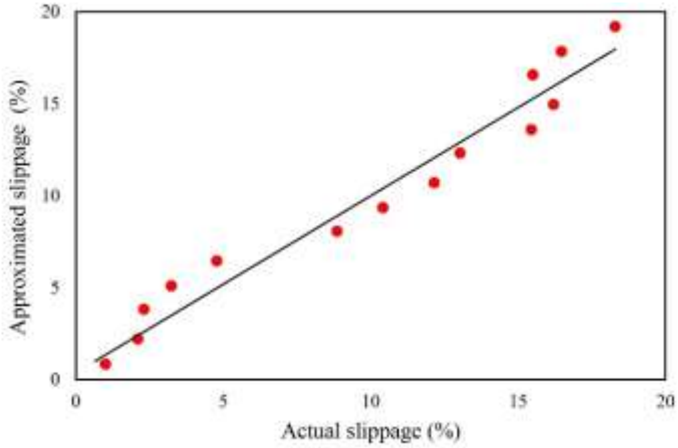

Figure 5. Relation between approximated and actual data of the slippage of the unmanned tracked vehicle

Figure 6 depicts projection area of the two-variable regressions onto horizontal plane and the regressions planes fitted to actual values of the slippage. According to the Figure 6, linear dependency of the slippage on both payload weight and the drive speed are understandable. Moreover, upward slope of the regression plane in the Figure 6 indicates synergistic increasing contributory effect of payload weight and the drive speed on the slippage. The projection area in the Figure 6 elucidates the slippage continuously changed over zones of 1-18 %. These findings are in excellent agreement with those reported in the previous Sections (statistical analysis).

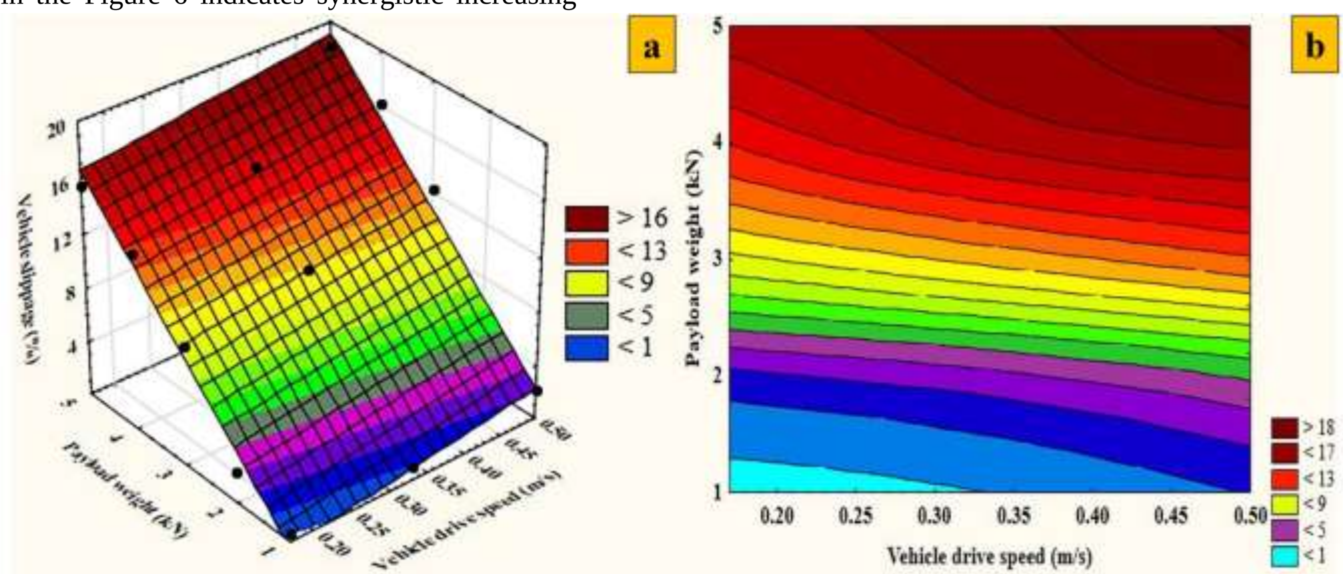

Figure 6. The two-variable regression planes fitted to actual data of the slippage (a) and projection area of the regressions onto horizontal plane (b) of the unmanned tracked vehicle

CONCLUSIONS

The current study comprises body of knowledge which is necessary to shed light into contribution of causative variables of payload weight (1-5 kN) and vehicle drive speed (0.17-0.5 m/s) to the slippage of the unmanned tracked vehicle in agricultural pulling tasks. The findings revealed consequential contribution of payload weight and the drive speed to the slippage. The contribution of payload weight to the slippage (0.64-18.30 %) was greater (37.91 times) than that of the drive speed.

The aforementioned contributions to the slippage were approximated by linear regression. The regression provides the equation for suppling of a view for designers and researchers in order to understand trends of the slippage as influenced by the consequential variables. Superior ability of the regression indicated linear dependency of the slippage on payload weight and drive speed.

Generally, numerical and analytical descriptions of the results as well as practical suggestions lead to appearance of a new perspective towards profound realization of the slippage of the unmanned tracked vehicle. This realization provides appropriate guidelines for vehicle supervisor in order to optimize slippage performance. According to accomplishment of pulling trails on concrete flat surface, it can be stated that the study results are specifically profitable for autonomous transportation of agricultural payloads in indoor and outdoor greenhouse constructions.

According to practical applications and theoretical knowledge obtained from the study outcomes, it is worthwhile to point out that state of the art has been improved in domain of the slippage of the unmanned tracked vehicle in agricultural pulling tasks. However, some challenges and future directions related to extension of the results for soil surface and the slippage in curvilinear motion of the vehicle are recommended for upcoming researches. Moreover, effect of track type (metal and rubber) on the slippage should be investigated, undoubtedly.

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