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THE INFLUENCE OF WIND ON AGRICULTURAL TRAILER STABILITY

Summary

This paper presents a simulation model of the farm tractor with a trailer. The aim of the study was the analysis of the effect of side wind gusts on agricultural trailer stability. Forces on roadway surface friction was taken into account. In the calculations different and varied weather conditions were assumed. Transport processes in agriculture affects the efficient functioning of farms. Results for various simulated weather conditions were presented. The results of the analysis will allow the rationalization of operational processes of agricultural machinery, which can improve the effectiveness of farm management.
Key words*: dynamic model, simulation model, stability, agricultural trailer, transport*

WPŁYW WIATRU NA STABILNOŚĆ RUCHU PRZYCZEPY ROLNICZEJ

Streszczenie

W pracy przedstawiono model symulacyjny zestawu transportowego składającego się z ciągnika rolniczego i przyczepy. Celem badań była analiza wpływu bocznych podmuchów wiatru na stabilność przyczepy rolniczej podczas jazdy, przy uwzględnieni tarcia na styku opony z jezdnią. W prowadzonych obliczeniach przyjęto różne i zmienne warunki atmosferyczne. Procesy transportowe w rolnictwie wpływają na sprawne funkcjonowanie gospodarstw. Dysponowanie wynikami analizy pozwoli na racjonalizację procesów eksploatacji maszyn rolniczych, co może przyczynić się do polepszenia wydajności prac w gospodarstwie.
Słowa kluczowe*: model dynamiczny, model symulacyjny, stabilność, przyczepa rolnicza, transport*

1. Introduction

Literature concerning the use of machines, specifies the influence of weather conditions, namely wind, as one of the main factors affecting driving safety and loss of stability of the machine. Especially, side wind gusts hinder the maneuvering of a vehicle and can lead to reduced control over the machine while driving. This problem applies to, inter alia, the transport sets, which include farm tractors with trailers. Due to the large side surface of the trailer, the forces generated by the impact of the wind, blowing in a perpendicular direction to the direction of driving, influence its stability while traveling. The speed of driving and the position of the center of gravity, especially of a loaded trailer, are essential while maneuvering on the road.

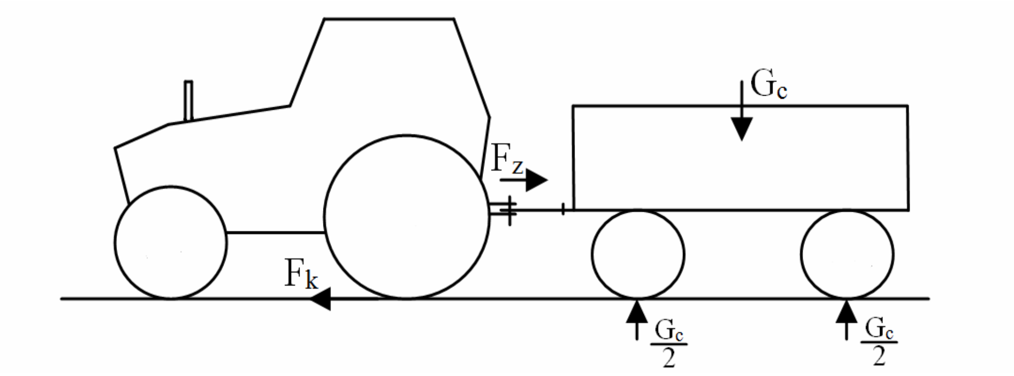
The article presents an analysis of agricultural trailer stability. Analyzed trailer was connected to the tractor. The loss of stability is defined as the increase of the force on the tire and road contact, resulting in a sideslip. At this point, the turning angle of the trailer's drawbar overruns the limit value, relatively to the longitudinal axis of the tractor. Mapping the conditions occurring during the passage of a machine set, requires the consideration of lateral friction occurring at the point of tire and road contact. The threshold of the friction force is defined as the amount of force required to break the side adhesion of the front tires. If the wind speed and the corresponding power take values greater than the friction force on the axis, it causes the slip of tires.

The aim of the research was to analyze the importance of side wind gusts on the stability of the moving agricultural trailer, including friction at the point of tire and road contact. The scope of the work included the analysis of stability, taking into account the influence of side wind gusts, speed of the vehicle, both frictional properties of the road and bending properties of the trailer and the tractor. It is necessary to indicate that together with the speed, the ease of being influenced by the side wind gusts increases, too. In adverse conditions, namely wet or icy road, the friction on the point of contact between the tire and the road, reduces significantly. In both cases, it is necessary to reduce the speed of machines. In the analysis it is difficult to predict the driver's reaction. This causing that his impact on the phenomenon will be omitted.

2. Material and methods

The research used properly modified methodology, which was formerly applied for trucks. This methodology is based on equations which enable the designation of forces and motion of the trailer, as well as facilitating the change of its position caused by the side wind gusts [6]. At the same time it was verified whether this method can be used to study the transport units, namely the farm tractor with a trailer. Correlations between the analyzed factors were presented in a graphical form. The considered model consisted of stiff blocks connected with elements susceptible to wind gusts. The model consisted of an agricultural tractor (reduced to the body and two axes) and two-axle trailer (made up of the chest and the axis with its wheels). Figure 1 shows distribution of forces in analyzed model.

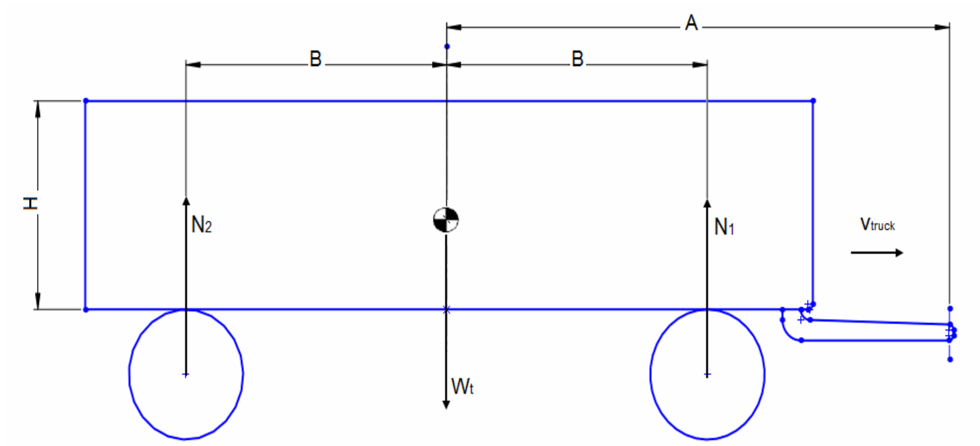
The analysis carried out on the model transport set, required determining the appropriate methodological assumptions. The analysis assumes that the tractor was moving in uniformly rectilinear motion. While moving, the trailer underwent the influence of side wind gusts, and the tractor functioned as a barrier at front, and ensured steady speed of driving. Wind gusts blew with constant speed, which reached the value of 0 $m \cdot s^{-1}$, in the end. The force caused by wind blasts had an uniform character on the whole side surface of the trailer. The road surface was perfectly flat and the roadway surface friction coefficient between the road



Source: own study based on [6] / Źródło: opracowanie własne na podstawie [6]

Fig. 1. Diagram of forces distribution in trailed aggregate: Gc – total weight machine and cargo, Fk – circumferential force on drive wheels, Fz – drawbar pull at the tractor hitch [5]

Rys. 1. Schemat rozkładu sił w agregacie przyczepianym: G_c – masa całkowita maszyny i ładunku, F_k – siła obwodowa na kołach napędowych, F_z – siła uciągu na zaczepie ciągnika [5]



Source: own study based on [6] / Źródło: opracowanie własne na podstawie [6]

Fig. 2. Schematic layout of analyzed forces and variables in the model: A – distance between the front hitch pin and the center gravity of the trailer, B – distance between trailer wheels axles and the center gravity of the trailer, H – trailer height, $N_{1,2}$ – axle load, W_t – trailer weight, v_{truck} – trailer speed

Rys. 2. Schemat rozmieszczenia analizowanych sił i zmiennych w modelu: A – odległość pomiędzy sworzniem zaczepu przedniego a środkiem ciężkości przyczepy, B – odległość pomiędzy osiami kół przyczepy a środkiem ciężkości przyczepy, H – wysokość skrzyni ładunkowej, $N_{1,2}$ – siły na osi przedniej i tylnej przyczepy, W_t – ciężar przyczepy, v_{truck} – prędkość jazdy

and the tire was permanent. Tires were incompressible and were not subjected to lateral attrition. The mass was examined at a point positioned in the center of gravity of the agricultural trailer.

One of the possible cases have been analyzed in the article. The analysis was conducted under the most severe road conditions, namely icing. The transport set, which was examined, was moving at speed of about 11 m·s^{-1}, whereas the wind speed reached limits between 20-30 m·s^{-1}. Model of transport set based on the progressive during the simulation. The movement of the trailer characterized whole transport set. Take into account the pressure exerted by the air on the side surface of the trailer, aerodynamic lift force perpendicular to the direction of travel, torques on the axles of the trailer, angles of rotation of the trailer relative to the original position, displacement of the rear axle, and lateral displacement resulting in a shift. The speed of the trailer was determined by the maximum speed of rotation and lateral displacement. In order to determine the forces, movement and repositioning of the trailer used in the following equations accorded to [1, 3, 4].

Bernoulli's equation was used to determine the pressure exerted by the air on the side surface of the trailer:

$$\text{pressure} = 1/2\ \rho\ v^2_{wind}, \tag{1}$$

ρ – air density,
v_{wind} – wind speed.

From equation (1) aerodynamic lift force acting perpendicular to the direction of the trailer was determined as follows:

$$F_L = 1/2\ \rho \cdot C_L \cdot (v^2_{wind} + v^2_{truck}) \cdot L \cdot W_d, \tag{2}$$

F_L – aerodynamic lift force,
ρ – air density,
C_L – aerodynamic lift coefficient,
v_{wind} – wind speed,
v_{truck} – trailer speed,
L – trailer length,
W_d – trailer width.

Aerodynamic force acting on the trailer was defined as:

$$F_D = 1/2\ \rho \cdot C_D \cdot v^2_{wind} \cdot L \cdot H, \tag{3}$$

F_D – aerodynamic side force,
ρ – air density,
C_D – aerodynamic drag coefficient,

v_{wind} – wind speed,
L – trailer length,
H – trailer height.

Then set torques occurring on the axles of the trailer and the equation of static equilibrium:

$$\Sigma M_1 = W_t \cdot B - F_L \cdot B - N_2 \cdot 2B = 0, \quad (4)$$
$$\Sigma M_2 = - W_t \cdot B + F_L \cdot B + N_1 \cdot 2B = 0, \quad (5)$$
$$N_{1,2} = N_1 = N_2 = (W_t \cdot B - F_L \cdot B) \cdot (2B)^{-1} = 1/2\,(W_t - F_L), \quad (6)$$

M_1 – torque acting on the front drawbar pin,
M_2 – torque acting on the axle of the trailer,
$N_{1,2}$ – axle load,
W_t – trailer weight,
B – distance between trailer wheels axles and the center gravity of the trailer,
F_L – aerodynamic lift force.

In order to create conditions in which the front axle of the trailer will slide sideways is required to take into account the friction force on the tire contact with the road:

$$\Sigma M_1 = F_{D,TH} \cdot A - \mu \cdot N_1 \cdot (A - B) - \mu \cdot N_2 \cdot (A + B)\,, \quad (7)$$
$$F_{D,TH} = (\mu \cdot 2\,N_{1,2} \cdot A) \cdot A^{-1} = 2\,\mu \cdot N_{1,2}, \quad (8)$$

M_1 – torque acting on the front drawbar pin,
$F_{D,\,TH}$ – aerodynamic side force acting on the threshold,
A – distance between the front hitch pin and the center gravity of the trailer,
B – distance between trailer wheels axles and the center gravity of the trailer,
μ – roadway surface friction coefficient,
$N_{1,2}$ – axle load.

Wind speed and the corresponding forces must be greater than the frictional force referred to above will slip on the axis of the tire:

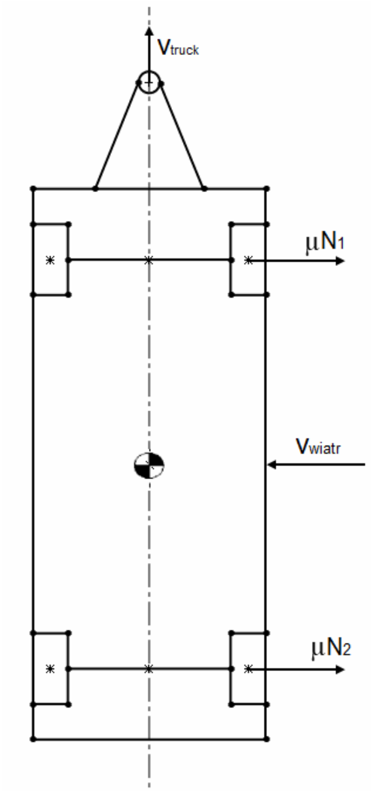
$$F_{D,\,TH} < F_D\,. \quad (9)$$

3. Results and discussion

Driving stability and potential loss of maneuverability underwent a research. Both issues resulted from the displacement of the trailer along the vertical axis to the tractor. The study focused on the influence of the reduced friction at the point of contact of the tire and road. It also considered the impact of speed and wind gusts strength. A suitable model, was developed in order to describe the discussed mechanical phenomena. Figures 2 and 3 show schematic layout of analyzed forces and variables in the model. The next step was to assign the trailer's dislocation towards the tractor, which was influenced by different values of wind power, as shown in Figure 4.

The most significant in this research was the question of displacement of the trailer. The phenomenon was defined as the sum of lateral displacement and the rotation at the front hitch pin [2]. Displacements and rotations calculated separately and combined, as shown in Figure 5.

Parameters used for the calculation according to literature [3, 4], were listed in Table 1.



Source: own study based on [6] / Źródło: opracowanie własne na podstawie [6]

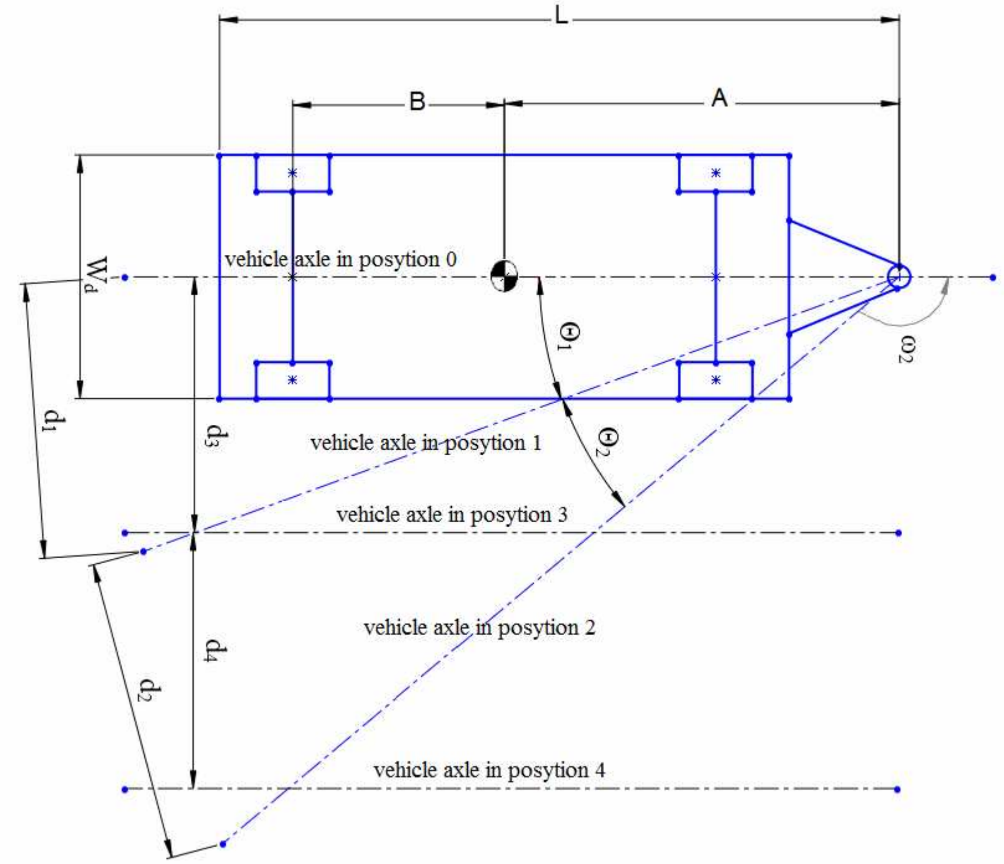
Fig. 3. Diagram of forces on roadway surface friction: v_{wiatr} – wind speed, μ – roadway surface friction coefficient
Rys. 3. Schemat z zaznaczonymi siłami występującymi na styku opony z jezdnią: v_{wiatr} – prędkość boczna wiatru, μ – współczynnik tarcia na styku opony z jezdnią

Table 1. Data used for the calculation
Tab. 1. Dane przyjęte do obliczeń

Specification	Value
Distance between front hitch pin and center gravity of trailer A [m]	4,26
Distance between trailer wheels axles and center gravity of trailer B [m]	1,50
Trailer height H [m]	1,80
Trailer width W_d [m]	2,39
Trailer length L [m]	4,44
Trailer mass m [kg]	4180,00
Trailer speed v_{truck} [$m \cdot s^{-1}$]	11,11
Air density ρ [$kg \cdot m^{-3}$]	1,22
Wind gusts time t_w [s]	3,00
Roadway surface friction coefficient μ [-]	0,20
Aerodynamic drag coefficient C_D [-]	2,00
Aerodynamic lift coefficient C_L [-]	1,00

Source: own study / Źródło: opracowanie własne

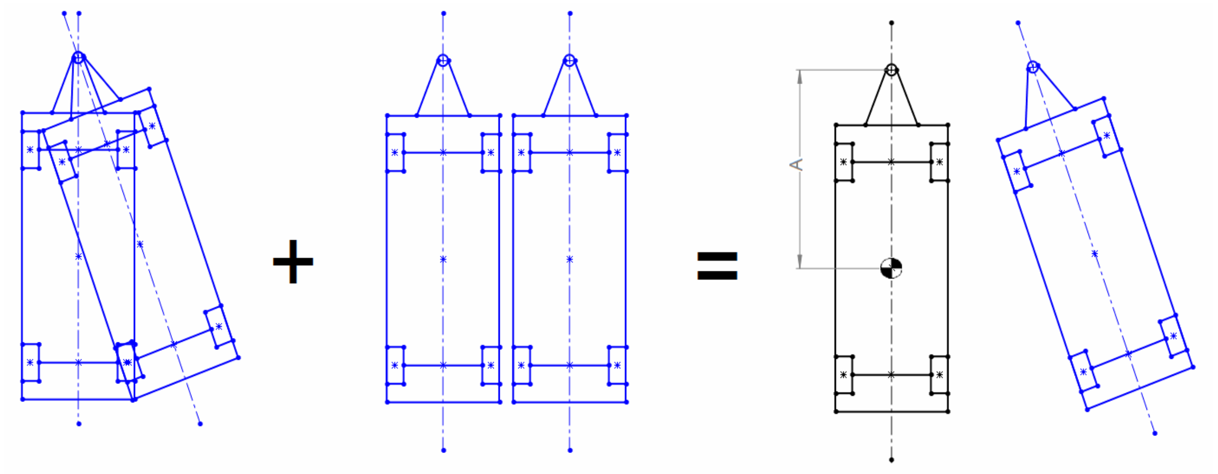
The calculation results are summarized in Table 2. It is inadvisable to cause a slack in the research, due to the specific character of the field works, which concern the use of transport sets in agriculture. The seasonal character of the work requires a balanced arrangement of agro-technological periods. Interruptions caused by traffic accidents, have a disadvantageous impact on the work organization and they unfavorable influence on economic aspects of the agricultural activity.



Source: own study based on [6] / Źródło: opracowanie własne na podstawie [6]

Fig. 4. Diagram of agricultural trailer possible displacements due to wind gusts: L - trailer length, W_d - trailer width, d_1 - displacement of the trailer $0 \le t \le t_w$, d_2 – displacement of the trailer $t_w \le t \le t_{nd}$, d_3 - displacement of the trailer in lateral direction $0 \le t \le t_w$, d_4 - displacement of the trailer in lateral direction $t_w \le t \le t_{nd}$, ω - the speed of cross-slip of tire, ω_0 - rotational speed t = 0 s, ω_1 - rotational speed $t = t_w$, ω_2 - rotational speed $t = t_{nd}$, Θ_1 - angle by which the trailer rotate at time of $t = t_w$, Θ_2 - angle by which the trailer rotate at time of $t = t_{nd}$ (where: t_{nd} - time without wind gusts, t_{nw} - time interval without wind gusts, t_w - wind gusts time)

Rys. 4. Schemat możliwych przemieszczeń przyczepy rolniczej na skutek bocznych podmuchów wiatru: L - długość przyczepy, W_d - szerokość przyczepy, d_1 - przemieszczenie tylnej osi wynikające z obrotu przyczepy $0 \le t \le t_w$, d_2 - przemieszczenie tylnej osi wynikające z obrotu przyczepy $t_w \le t \le t_{nd}$, d_3 - odległość o jaką przyczepa przesunęła się w kierunku bocznym $0 \le t \le t_w$, d_4 - odległość o jaką przyczepa przesunęła się w kierunku bocznym $t_w \le t \le t_{nd}$, ω - prędkość poprzecznego poślizgu opony, ω_0 - prędkość obrotu w czasie t = 0 s, ω_1 - prędkość obrotu w czasie $t = t_w$, ω_2 - prędkość obrotu w czasie $t = t_{nd}$, Θ_1 - kąt o jaki obróci się przyczepa w czasie $t = t_w$, Θ_2 - kąt o jaki obróci się przyczepa w czasie $t = t_{nd}$ (gdzie: t_{nd} - czas bez podmuchów wiatru i bez bocznych przemieszczeń, t_{nw} - przedział czasu w którym brak podmuchów wiatru, t_w - czas trwania podmuchów)



Source: own study based on [6] / Źródło: opracowanie własne na podstawie [6]

Fig. 5. Diagram for calculating the sum of lateral displacement and the rotation of agricultural trailer

Rys. 5. Schemat obliczania obrotów i przemieszczeń przyczepy rolniczej

Table 2. Wind influence on agricultural trailer stability
Tab. 2. Wpływu podmuchów wiatru na stabilność ruchu przyczepy rolniczej

Wind speed v_{wiatr} [m·s^{-1}]	Aerodynamic side force F_D [N]	Aerodynamic lift force F_L [N]	Axle load $N_{1,2}$ [N]	Rotational speed ω_1 [rad·s^{-1}]	Trailer lateral slip speed v_{1cg} [m·s^{-1}]	Displacement				Resultant displacement d [m]
						d_1 [m]	d_2 [m]	d_3 [m]	d_4 [m]	
20,0	3900,0960	3388,2158	18808,792	0	0	0	0	0	0	0
20,5	4097,5384	3519,2956	18743,252	0	0	0	0	0	0	0
21,0	4299,8558	3653,6119	18676,094	0	0	0	0	0	0	0
21,5	4507,0484	3791,1647	18607,318	0	0	0	0	0	0	0
22,0	4719,1162	3931,9541	18536,923	0	0	0	0	0	0	0
22,5	4936,0590	4075,9801	18464,910	0	0	0	0	0	0	0
23,0	5157,8770	4223,2426	18391,279	0	0	0	0	0	0	0
23,5	5384,5700	4373,7416	18316,029	0	0	0	0	0	0	0
24,0	5616,1382	4527,4771	18239,161	0	0	0	0	0	0	0
24,5	5852,5816	4684,4492	18160,675	0	0	0	0	0	0	0
25,0	6093,9000	4844,6579	18080,571	0	0	0	0	0	0	0
25,5	6340,0936	5008,1030	17998,848	0	0	0	0	0	0	0
26,0	6591,1622	5174,7847	17915,508	0	0	0	0	0	0	0
26,5	6847,1060	5344,7030	17830,549	0	0	0	0	0	0	0
27,0	7107,9250	5517,8578	17743,971	0,002	0,007	0,02	0,00	0,01	0,00	0,03
27,5	7373,6190	5694,2491	17655,775	0,052	0,223	0,45	0,04	0,34	0,01	0,84
28,0	7644,1882	5873,8769	17565,962	0,104	0,443	0,90	0,16	0,67	0,06	1,78
28,5	7919,6324	6056,7413	17474,529	0,157	0,667	1,35	0,36	1,00	0,13	2,84
29,0	8199,9518	6242,8423	17381,479	0,210	0,895	1,81	0,65	1,34	0,24	4,04
29,5	8485,1464	6432,1798	17286,810	0,264	1,127	2,27	1,04	1,69	0,38	5,38
30,0	8775,2160	6624,7538	17190,523	0,320	1,363	2,74	1,52	2,04	0,56	6,87

Source: own study / Źródło: opracowanie własne

Analysis of the data in Table 2 leads to the conclusion that in terms of safety of driving, and thereby stability of motion, of the discussed transport set, it is important to mention that there are wind gusts reaching over 27,0 m·s^{-1}, without regard of the research. With the wind speed reaching over 30,0 m·s^{-1}, the resultant displacement reaches the value of 6,87 m, unequivocally suggesting loss of control over the running course of the transport set. With the increase of the wind power, the forces occurring on the trailer's front and rare axles decrease. The loss of stability caused by a skid occurs when the product of the contact force per trailer's axle and the friction at the point of contact between tires and the road, is exceeded.

4. Summary

The research and analysis allows to formulate the following conclusions:

1. It has been proved that the model described for the farm tractor with a trailer meets the relevant requirements. By using considered method, it is possible to identify and determine safe speeds for presented transport set.
2. Designed and described dynamic model can be used for more complex research and experiences, taking into account the various weather conditions, not only the wind.

5. References

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