



# Article Research Determining the Priority Order of Forces Acting on a Vehicle Transporting Logs

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Abstract: When transporting different types of cargo, the factors affecting the cargo must be assessed to ensure a safe and fast transportation process. However, the specificity of the cargo means that the standard assessment methods do not reflect the existing conditions or are standard at the theoretical and/or recommendation level. Therefore, in the event of a traffic accident, when a vehicle or cargo is damaged or other traffic participants are put at rink, assessment of the situation is difficult and requires an expert assessment. Then, the most optimal means of accomplishing this is to simulate transportation parameters with a specific vehicle and cargo. The transportation of wooden logs is a very specific method of transportation where, in addition to the weight of the load itself, it is necessary to assess how the load affects the dynamics of the vehicle. Therefore, determining the priority of the forces that act on the vehicle carrying wooden logs becomes very important in order to model the transport parameters of this cargo. This article uses an analytical survey, an expert survey and its analysis, and methods to determine correlations. Given the fact that the main forces acting on the load most often manifest during a turn, this study assessed road turns and the respective speed on them as the main parameters. Other parameters, such as road roughness and roundabouts, were not assessed, because they would be an object of long-distance research. The study results revealed that the main forces affecting a vehicle transporting logs manifest in the following priority order: inertial forces, gravity forces, frictional forces and, finally, centrifugal forces.

**Keywords:** wood log transportation; inertial forces; gravity forces; frictional forces; centrifugal forces; expert survey; correlation; pearson coefficient

# 1. Introduction

Freight transportation is an important element of the logistics supply chain [1], especially when taking into account the elements of reliability of supply. There are many aspects that affect the reliability indicators in cargo transportation [2]. This includes the chosen vehicle, the placement of the load itself, its fastening, and its weight. Some aspects are of minor importance in assessing the transportation process itself, e.g., the wear and tear of the fastening elements, which can be minimised by performing the necessary maintenance [3]. Therefore, the arrangement and mass of the cargo, as well as the dynamic indicators of the vehicle itself, are the most important factors [4].

The energy of cargo movement is a threatening force, the impact of which can be avoided only by strictly following certain requirements [5]. The effect of this force on the side structures of the vehicle body on which the loads rest is of particular concern [6]. However, undesirable consequences, which sometimes may even be tragic, can be avoided by using specially adapted vehicle body structures and the reliable fastening of loads [7].



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**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). This is especially important when transporting specific cargo [8]. This article examines the reliability of wood log transportation [9].

A rational cargo arrangement scheme is selected in each specific case depending on the type of cargo, container, and vehicle body dimensions [10]. The cargo must be placed in the cargo compartment according to the following requirements [11]:

- The cargo must be placed as evenly as possible throughout the entire floor area of the cargo compartment;
- It must be placed as low as possible. The center of gravity of the cargo must be as close to the line of the longitudinal axis of symmetry of the cargo compartment as possible;
- The cargo must be supported on the front side of the compartment or on the protective structure of the cab, as well as on the sides of the cargo compartment;
- Loads with sharp ends must be placed with the sharp end facing towards the rear.

A load must be secured so that, while the vehicle is moving, it cannot be released by the following forces (Figure 1) [12]:

- Inertial force directed in the direction of movement, the impact of which is equal to 0.8 F<sub>G</sub>;
- Lateral and backward inertial force of 0.5 F<sub>G</sub>.



Figure 1. Distribution of inertial forces.

The European Commission states that the top of the logs in the middle should be higher than that of logs on the sides to allow the load to be properly fastened, as shown below [13]. The logs should rest on a conical wedge or a toothed brim [14].

A trailer connector should be installed in the front of the first section of logs, between the driver's cabin and the logs. The strength must meet the requirements of the EN 12642 XL standard [15] and the load should not be higher than the front of the vehicle. Ropes or similar means of fastening should be tied across the top of each load section (stack of logs) to ensure vertical compression of the logs; the number of ropes should be as follows [14,16]:

- (a) At least one rope if the cargo section consists of logs with bark and if the length of the log does not exceed 3.3 m;
- (b) At least two ropes if the load section is longer than 3.3 m or if the bark has been removed, regardless of the length of the logs.

The overhead lashing ropes must be (transversely) lashed between the front and thee rear pillars of each cargo section, ensuring as much symmetry as possible [17]. More ropes should be used in vehicles that do not have a side of sufficient strength or automatic tensioning means, i.e., using two ropes if logs are not longer than 3 m, three ropes if logs are up to 5 m long, and four ropes if logs are longer than 5 m [18].

Wood is a living product that constantly moves during transportation [19]. During transportation, wood is exposed to external forces, so its fastening equipment must be chosen accordingly. General principles should apply to load distribution, ensuring that the

load is stable at the front wall. The front wall should be installed according to the EN 12642 XL class standard, and the load should not protrude the front wall.

Before transporting wood, a loaded stack of wood must be fixed in the vehicle using special belts of at least 50 mm wide [20]. The breaking force indicated on the belt label must be at least 5000 kg. All belts should withstand a minimum tensile force of 1600 daN. A self-tensioner should be used, which makes it easier to fix the wood to the base, ensuring stronger support.

The use of chain or mesh fastening with turnbuckles is recommended, and all belts should be checked and kept taut throughout transport [21]. Each outer piece of wood should be supported by at least two or three perpendicular posts. The strength of the pillars should be sufficient to prevent the vehicle from exceeding the width restrictions.

Logs that are shorter than the distance between the two supporting posts should be loaded at the centre of the load [19]. When there are two pairs of supports supporting wood, their ends should protrude at least 300 mm from the supports. The distance between the wood and the road surface should be at least 0.6 m [22].

When transporting wood in a vehicle with temporarily installed supports, the height of the loaded wood stack cannot exceed 1.6 m from the bottom of the supports [23]. Cushions must be equipped with latches to prevent them from sliding toward the edges [24].

The overhead bracing that creates vertical pressure on the wood should be tightened in each load section at the following points [25]:

- (a) Barked wood: at least one strap per load section up to a maximum length of 3.3 m, with two belts if the cargo section is longer than 3.3 m.
- (b) Barkless wood: at least two lashing straps per load section.

Wood must be transported within the maximum permitted vehicle dimensions, the maximum axle loads (s), and the maximum allowed gross weight, approved by Order No. 3–66 of the Minister of Transport of 18 February 2002 "On the approval of the maximum permitted dimensions of vehicles, the permitted axle loads (axle), the allowed gross mass" (2002, No. 23–870), and the weight that a vehicle (combination) can carry [26].

To assess the reliability of transport carrying this type of cargo, special instructions are followed, without performing a reliability assessment. The scientific literature does not distinguish any specialized approach to reliability in log transport, which leads to the conclusion that reliability research in log transport is not widespread.

The fact that the most common interaction between cargo fastening and acting forces is assessed at the theoretical level only, and the entire arrangement of the technological process of cargo fastening and transportation is more of a recommendation than a justification for practical application, creates an unprecedented need for this kind of actual, mathematical, calculation. Thus, the aim of this article is to restore the practical situation and provide reliable calculations that can assess the forces acting in a mathematical expression and determine the priority order of the forces acting on the vehicle transporting logs. The obtained results are unique and emphasize the innovative and scientific nature of the obtained results. These calculations were made by taking factors of speed and road turns into account, since this is when most cases of cargo- and/or vehicl—overturning occur, causing damage to the vehicle and cargo, and when the load may also damage the road and its infrastructure elements and put other traffic participants in danger. Such road elements as roundabouts and islands are also important, but they were not considered in the calculations, since, in this case, the speed and the turning angle are significantly lower than in the above-mentioned cases.

# 2. Materials and Methods

When assessing reliability, the main criteria that have a significant impact on the transportation of logs were distinguished in this article. These include vehicle dynamics' parameters, such as centrifugal force, critical slip, roll, and vehicle speed [27].

The impact of the centrifugal force can be controlled. The centrifugal force is calculated according to the following formula [28]:

$$F = \frac{mv^2}{r} \tag{1}$$

where *F* is the centrifugal force;

*m*—mass;

*v*—speed;

*r*—radius.

The centrifugal force of the vehicle occurs during [27]:

- A sudden braking;
- Suddenly starting to drive;
- When driving in a corner.

The centrifugal force increases with increasing driving speed and lower road turn radii. With a reduction in the speed at a corner, the centrifugal force also decreases [29].

When turning, the centrifugal force pushes a vehicle away from the centre of the turning curve. The impact on the vehicle depends on which part of the vehicle is affected the most by this force. If it mainly affects the upper part of the vehicle, this lateral movement of the vehicle is difficult to control, and if it affects the lower part, the movement of the chassis and body will be minimal and the vehicle will be more stable [30].

The load's kinetic (movement) force is opposite to the frictional force, which depends on the load's composition, shape, dimensions, and contact with the platform. The drag force is calculated using the coefficient of friction and the weight of the load. The magnitude of the friction force coefficient is usually between 0.01 (load on wet floor) and 0.5 (dry wood on dry wood floor). The difference between weight (mass) and friction forces forms the minimum amount of fastening force that ensures a stable holding of the load [31].

The force of gravity is calculated according to Newton's second law. Table 1 shows the sliding friction of various materials [32], which are used to calculate the load-securing according to a simplified formula. This table was compiled by the author, based on/guided by the "Requirements for load arrangement and/or its attachment in category N and O vehicles" [26].

Table 1. Slip coefficient of the vehicle floor.

Floor of the Cargo Compartment of the Vehicle	Cargo			
Fibbl of the Cargo Compartment of the venicle	Dry	Wet	Oiled	
Wood/wood	0.20-0.50	0.20-0.25	0.05-0.15	
Metal/wood	0.20-0.50	0.20-0.25	0.02-0.10	
Metal/metal	0.10-0.25	0.10-0.20	0.01-0.10	
Concrete/wood	0.30-0.60	0.30-0.50	0.10-0.20	

The critical slip of the vehicle was calculated according to the formula [27,28]:

$$v_{\rm sl} = \sqrt{\frac{(\cos\beta \cdot \phi_s - \sin\beta) \cdot g \cdot R}{\cos\beta + \sin\beta \cdot \phi_s}} m/s \tag{2}$$

where *R*—the turning radius of the road,

*g*—free fall,  $g = 9.81 \text{ m/s}^2$ ;

 $\varphi$ s—coefficient of adhesion to the road surface.

Critical tumble of the vehicle [27,28]:

$$v_{\rm T} = \sqrt{\frac{(\cos\beta \cdot 0.5 \cdot B - \sin\beta \cdot h)g \cdot R}{\cos\beta \cdot h + \sin\beta \cdot 0.5 \cdot B}}m/s$$
(3)

where *R*, the turning radius of the road,

*h*—height of the centre of gravity (empty/loaded), mm;

*B*—width of the intercostal space, m;

*g*—acceleration of free fall,  $g = 9.81 \text{ m/s}^2$ ;

 $\varphi_s$ —coefficient of adhesion to the road surface.

The centrifugal force is the force that pushes a rotating body away from the centre of rotation. It depends on the object's mass, rotation speed, and distance from the centre [33]. The centrifugal force increases with increasing driving speed and fewer radii of road bends. With a reduction in the speed at a corner, the centrifugal force will decrease. The movement forces are the key thing to take into account when choosing the appropriate fastening equipment [34].

A Volvo FH truck (Gothenburg Sweden) was used in the research. The truck is equipped with an "I-Shift" gearbox (using the "I-SEE" system), an independent front suspension, and a dynamic steering system.

Alucar OY superstructure was chosen for wood transportation. Alucar Oy is a part of Extendo Group, a Swedish company that specialises in the field of timber transport and load fastening, and the design of superstructures and supports for logging trucks. The manufacturers of these superstructures aim to obtain the maximum payload, thus ensuring high quality. The parts of these superstructures are manufactured in such a way that they can be assembled quickly and easily, and require as little welding as possible [35].

Screw connections allow for spare parts to be replaced very quickly. The supports of this superstructure are made of steel, the carrying capacity of which is 7 tons. The supports are cast in conical struts with a length of 2850 mm. The uprights are installed using a steel wedge and attached to the superstructure supports using screws.

The protective wall of the structure is made of double-walled anodised aluminium profiles that are connected to each other using strong profile connections [36]. The structure withstands collisions with logs and their scratching very well [37], as there are no remaining bends. The superstructure is resistant to corrosion, as the supports and struts are coated in a thick zinc primer and painted with powder paint. This superstructure is perfectly adapted to extremely complicated and difficult road conditions.

#### 3. Results

Analytical calculations were performed using roundabout radii. The radius of the roundabout varies from 5.3 to 17 m. A fully loaded vehicle carrying a load of wood (its force action vectors are presented in Figure 2), traveling at a speed of 20 km/h through a 5.3 m roundabout, is affected by the centrifugal force presented in Table 2.



Figure 2. Direction of the force of the centre of gravity under the influence of the centrifugal force.

Table 2. Comparative calculation of forces.

Type of Force	Calculated Value
Centrifugal force	$F = \frac{40,000 \cdot 30.8}{5.3} = 232,452.8 N$
Gravity force	F = 40,000 \cdot 9.81 = 392,400 N

The calculations found that a vehicle driving through a roundabout with a radius of 5.3 m is affected by a centrifugal force of 232,452.8 N.

The force exerted on a vehicle was calculated. When the centrifugal force exceeds the force of gravity, the vehicle rolls over. This in illustrated in the graph of the dependence of centrifugal force on speed, shown below (Figure 3).





Figure 3 shows that when a vehicle travels at the speed of up to 25 km/h, it is stable, which means that the effect of the centrifugal force does not exceed the gravity force. However, when a vehicle's speed is greater than 25 km/h, the centrifugal force exceeds the force of gravity, resulting in the truck overturning.

The critical slope of a truck was calculated using the asphalt friction coefficient, the turning radius, and the transverse slope of the road. The asphalt friction coefficient is the most important criterion, and dry asphalt of  $\mu = 0.6$ , a turning radius of 5.3 m, and a cross-slope of the road of  $\beta = 2$  [28] were used in the calculation.

$$v_{\rm sl} = \sqrt{\frac{(0.999 \cdot 0.6 - 0.034) \cdot 9.81 \cdot 5.3}{0.999 + 0.034 \cdot 0.6}} = 5.37 \,\mathrm{m/s} \tag{4}$$

A critical truck skid does not occur until the speed reaches 19 km/h [38]. However, when the truck speed exceeds 19 km/h, the truck will start to slide at this asphalt friction coefficient during the turn.

The critical fall of a truck is calculated considering the width of the vehicle track and the height of the load's centre of gravity. The width of the rut of a wooden structure is 2.55 m. The selected height of the centre of gravity of the load is 2.05 m from the ground when the vehicle is loaded, while the selected center of gravity of the unloaded vehicle is 1.2 m [28].

Loaded vehicle:

$$v_T = \sqrt{\frac{(0.999 \cdot 0.5 \cdot 2.55 - 0.034 \cdot 2.05) \cdot 9.81 \cdot 5.3}{0.999 \cdot 2.05 + 0.034 \cdot 0.5 \cdot 2.55}} = 5.83 \text{ m/s}$$
(5)

Empty vehicle:

$$v_T = \sqrt{\frac{(0.999 \cdot 0.5 \cdot 2.55 - 0.034 \cdot 1.2) \cdot 9.81 \cdot 5.3}{0.999 \cdot 1.2 + 0.034 \cdot 0.5 \cdot 2.55}} = 7.17 \text{ m/s}$$
(6)

The critical rollover speed of a loaded and empty vehicle at a 5.3 m roundabout is estimated in Figure 4. A loaded vehicle will roll over at a speed of more than 21 km/h, and an empty vehicle will roll over at a speed of more than 26 km/h.





Figure 4 illustrates the dependence of the speed and height of the center of gravity. The critical turning point is where the turning speed and the sliding speed curves meet. In this case, a vehicle will roll over when the height of the centre of gravity of the vehicle is 2.4 m from the ground and the speed of the vehicle is 19 km/h.

# 4. Discussion

Observations, calculations, and tests were conducted using an inclined plane test bench in the research, analysing the effect of centrifugal force on vehicle dynamics [39]. How the centrifugal force works has been determined, as well as the speed and the turning angle at which a truck can overturn, which are significantly affected by the load's centre of gravity.

Figure 5 shows how the vehicle must be loaded correctly so as not to exceed the axle loads. The most important thing is to properly load the vehicle without exceeding its total permissible weight, properly arranging the load so as not to exceed the axle load, and securing it as required by the European load-securing rules. Properly secured transported loads are less affected by external forces.

The centre of any stack of forest material must not protrude above the supports. The middle part of the stack should be higher than the side, forming a "ridge" in the load and allowing the load to be properly fastened, as shown in the Figure below.

The most dangerous forces affecting heavy transport are as follows:

- Centrifugal force;
- Friction force;
- Gravity force;
- Inertial force.



Figure 5. Correctly and incorrectly loaded round wood.

During log transportation, forces affect both the load and the vehicle. These are usually seen as separate elements, and their priority and the complexity of their interactions are disregarded [40]. Twelve experts participated in the expert evaluation, assessing the impact of the forces (Table 3).

Table 3. Results of expert evaluation rankings.

Formula	Centrifugal Force	Gravity Force	Friction Force	Inertial Force
$\sum_{i=1}^{n} R_{ij} = R_{ij}$	36	28	32	24
$\overline{R}_{j} = \frac{\sum_{i=1}^{n} R_{ij}}{n}$	3	2.333	2.667	2.000
$\sum_{i=1}^{n} R_{ij} - \frac{1}{2}n(m+1)$	6	-2	2	-6
$\left[\sum_{i=1}^{n} R_{ij} - \frac{1}{2}n(m+1)\right]^2$	36	4	4	36

Balance is the most important factor when making an informed decision. Assessing the compatibility of expert opinions is an essential part of quality research. Therefore, to consistently assess the opinions of two or more experts, Kendall's correlation coefficient (W) is used, ranking experts' assessments (Table 4). The consistency of experts' opinions is defined when W approaches 1. Expert opinions are considered consistent when W1 and inconsistent when W approaches 0 [41].

Table 4. Results of calculations of the concordance coefficient.

Formula	Results
$W = \frac{12S}{n^2(m^3 - m)}$	0.1111
$\chi 2 = \frac{12S}{nm(m+1)}$	4.00
$W_{min} = rac{\chi^2_{v,a}}{n(m+1)}$	0.0162

The obtained results show that  $W > W_{min}$ . This suggests that the experts' opinions are consistent, and further calculations can be made, which can evaluate the order of the acting forces (Table 5).

Indicator Value	Centrifugal Force	Gravity Force	Friction Force	Inertial Force
$\overline{q} = rac{\overline{R}_j}{\sum_{j=1}^m R_j}$	0.3000	0.2333	0.2667	0.2000
$d_j = 1 - \overline{q}_j = 1 - \frac{\overline{R}_j}{\sum_{i=1}^m R_i}$	0.7000	0.7667	0.7333	0.8000
$Q_j = \frac{d_j}{\sum_{i=1}^m d_i} = \frac{d_j}{m-1}$	0.2333	0.2556	0.2444	0.2667
$\overline{Q}_j = rac{\sum_{i=1}^n B_{ij}}{\sum_{i=1}^n \sum_{j=1}^m B_{ij}}$	0.2000	0.2667	0.2333	0.3000
Arrangement of factors by importance	4	2	3	1

Table 5. Determining the priority order of the forces acting during log transportation.

The obtained results show that the importance of the forces acting during transportation is distributed in the following sequence:

- 1. Inertial force;
- 2. Gravity force;
- 3. Frictional force;
- 4. Centrifugal force.

It is important to note that acting forces make a vehicle uncontrollable. Gravity, centrifugal force and frictional force are laws of nature that affect vehicle loads. In road traffic, loads are always affected by physical forces.

The results revealed that the forces of inertia and gravity have the greatest impact. However, when evaluating the interaction and its strength among all forces, it is also important to find their dependence (Figure 6).

	Centrifugal force	Gravity force	Frictional force	Inertial force
Centrifug al force				
Gravity force			2	
Frictional force				····
Inertial force				

Figure 6. Correlational dependences of forces acting on a vehicle transporting logs.

The analysis of correlations reveals that there is a strong to moderate correlation between all the studied forces (judged by the values of the Pearson's correlation coefficient) (Table 6). A close to very strong correlation between centrifugal and inertial forces (0.93924), and gravity and frictional forces (0.99016), can be distinguished. A strong correlation is also observed between centrifugal and frictional forces (0.72439), and centrifugal and gravity forces (0.7315), while inertial and frictional forces (0.54059) and inertial and gravity forces (0.59001) demonstrate a moderate correlation.

	<b>Centrifugal Force</b>	<b>Gravity Force</b>	<b>Frictional Force</b>	<b>Inertial Force</b>
Centrifugal Force	1	0.7315	0.72439	0.93924
Gravity Force	0.7315	1	0.99016	0.59001
Frictional Force	0.72439	0.99016	1	0.54059
Inertial Force	0.93924	0.59001	0.54059	1

**Table 6.** Evaluation of correlation dependences of the forces acting on a vehicle transporting logs based on the Pearson correlation coefficient.

However, it should be noted that when examining the correlations between the forces, very strong and strong correlations created by the centrifugal force were observed. It should be noted that the centrifugal force depends on:

- The height of the centre of gravity, because the lower the center of gravity, the lower the effect of centrifugal force on the vehicle;
- Vehicle speed;
- The turning angle, because the steeper the turning angle, the stronger the effect of centrifugal force.

The stability of the vehicle depends on its speed. The faster the speed, the greater the braking distance, impact force and the turning radius. This means that when making a sharp turn at a speed of 30 km/h, the probability of a vehicle sliding and overturning is minimal, but if the vehicle is traveling at 60 km/h, the probability of risk increases by four times [28] (Figure 7).





When entering a turn at a speed of 90 km/h, the vehicle is exposed to a nine times stronger centrifugal force, which means that the probability of the vehicle overturning is high. The higher the speed, the greater the chance that the driver will lose control and the vehicle will lose control.

The direction of the friction force is opposite to the direction of motion of the body. The magnitude of the friction force depends on:

- Types of materials that come into contact with each other;
- Treatment of touching surfaces (irregularities);
- The vehicle body weight (mass).

Considering the above information, it is important to evaluate the interdependencies of the constituent criteria of friction and centrifugal forces (Figures 8 and 9) and the correlations (Tables 7 and 8).

	Position of center of gravity	Vehicle speed	Vehicle trajectory (steer angle)
Position of center of gravity			
Vehicle speed			
Vehicle trajectory (steer angle)			

Figure 8. Correlational dependences of components of centrifugal forces.

	Type of wood load in con- tact	Quality of wood in contact with the surface of the ve- hicle superstructure	Position of the center of gravity of the wood load
Type of wood load in contact		··	
Quality of wood in contact with the surface of the vehi- cle superstructure	· · ·		
Position of the cen- ter of gravity of the wood load			

Figure 9. Correlational dependences of components of friction forces.

 Table 7. Correlations of components of centrifugal forces.

	Position of the Center of Gravity	Vehicle Speed	Vehicle Trajectory (Steer Angle)
Position of the center of gravity	1	0.89924	0.64308
Vehicle speed	0.89924	1	0.91329
Vehicle trajectory (steer angle)	0.64308	0.91329	1

Table 8. Correlations between components of friction forces.

	Type of Wood	Quality of Wood in Contact with the Surface of	Position of the Center of Gravity
	Loud In Contact	the venicle Superstructure	of the fibbu Load
Type of wood load in contact	1	0.86487	0.99665
Quality of wood in contact with			
the surface of the vehicle	0.86487	1	0.90302
superstructure			
Position of the center of gravity of the wood load	0.99665	0.90302	1

In summary, according to Pearson correlation coefficient values, a strong and moderate correlation was observed between all the investigated centrifugal force factors. A close to very strong correlation between the vehicle speed and the vehicle trajectory (steer angle) (0.91329), and the vehicle speed and the position of the center of gravity (0.89924), can be distinguished. A strong correlation was also observed between the vehicle trajectory (steer angle) and the position of the center of gravity (0.64308).

An analysis of the correlations (according to the Pearson correlation coefficient values) revealed that a close to very strong and strong correlation between all the investigated factors of friction force. There is a close to very strong correlation between the type of wood load in contact and the position of the center of gravity of the wood load (0.99665), and the quality of wood in contact with the surface of the vehicle superstructure and the position of the center of gravity of the wood load in contact and the quality of wood load (0.90302), and a strong correlation between the type of wood load in contact and the quality of wood in contact with the surface of the vehicle superstructure (0.86487).

In the transportation for logs, the impact of forces is very important and could be further assessed by modelling this type of transportation. During this study, these criteria were determined according to the scheme presented in Figure 10.



Figure 10. Scheme of priority assessment of forces acting on vehicles transporting logs.

Considering the specificity of the load, the priority of manifesting forces may differ; therefore, when selecting multiple criteria for the importance of loads, this scheme comes in handy when making a reasonable evaluation of the criteria.

# 5. Conclusions

During the transportation of cargo, the vehicle and the cargo itself are constantly affected by various physical forces, including gravity, centrifugal, frictional and inertial forces. These forces can make a vehicle uncontrollable, manifesting when a vehicle moves on an uneven trajectory, and suddenly stops or accelerates.

During the experimental evaluation, the forces of inertia and gravity were found have the greatest impact during the transportation of logs.

Having determined the interaction and its strength among all forces, a dependence was established, showing a strong to moderate correlation between all the investigated forces. There is a very strong correlation between centrifugal and inertial forces (0.93924) and gravity and frictional forces (0.99016); a strong correlation was also observed between centrifugal and frictional forces (0.72439) and centrifugal and gravity forces (0.7315); a moderate correlation was observed between inertial and frictional forces (0.54059) and inertial and gravity forces (0.54059).

Having analysed the factors on which the trinity and the centrifugal force depend, the interdependence and correlations of the factors were assessed, which showed a strong and medium correlation between all factors of the centrifugal force and a close-to-strong and strong correlation between all the factors of the trinity force.

Future research directions could involve the assessment of different forces by modelling various transportation situations, as well as the assessment of other types of cargo. Road elements such as roundabouts and islands were not considered because their speed and turning angle are significantly lower than in the analysed case. Inherent characteristics of the vehicles chassis and suspension could also be researched as complex road conditions, and they could also be the direction of long-range calculations and practical simulations. Another direction of scientific research could be associated with the evaluation of these parameters through the use of methodologies such as machine learning and fuzzy systems, such as artificial intelligence [42,43], which could improve such calculations.

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