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THE EFFECT OF A MALFUNCTIONING BRAKING SYSTEM ON THE BEHAVIOUR OF A SPECIAL VEHICLE DURING AN EMERGENCY BRAKING IN A CURVILINEAR MOVEMENT

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Abstract. Vehicle mobility is an increasingly important issue today, even in the military field. Mobility depends on the condition of the vehicle, the route and, of course, the experience of the driver. Vehicle failures and damage are very common in military operations. It is therefore important to find out how these failures and damage can affect mobility. One of the essential parts of a vehicle is the braking system. The authors therefore decided to investigate what is the effect of a malfunctioning brake system on emergency braking behaviour of a special vehicle in a curvilinear movement. Simulation tests were performed based on an experimentally validated model. The tests were performed with a wheeled vehicle on three different surfaces: concrete, wet asphalt, and ice. The experimental conditions were given as follows – the braking process was considered for a braking system with ABS on and off and for two states of braking system sufficiency (8 braked wheels or 4 rear braked wheels). These tests allowed us to analyse the effect of the extent of the damage on safety, in this case the stopping of the vehicle on a specified curved route. The results of braking and stability on different surfaces and under given conditions are evaluated and described in this paper. On the basis of the results, it is possible to prepare training programmes (scenarios) for drivers of special vehicles for the purpose of driving techniques in critical situations.

Keywords: Mobility, vehicles, braking systems, ABS, multiaxial dynamic simulation model.

1. Introduction

Military wheeled vehicles must be characterised by a high level of traction features. The ability to move at high speed in changing conditions is one part of soldier safety. A side effect of dynamic driving can be a loss of stability [1]. One of the manoeuvers during which a dangerous event can occur is cornering. When going through curves at high speeds and braking simultaneously [2], wheeled vehicles in particular are subject to a loss of stability [3, 4]. In addition, military vehicles, especially combat vehicles, are subject to damage to the braking system, and therefore a braking manoeuvre during a cornering can be particularly dangerous [5].

2. Threat to the safety of military wheeled vehicles

In relation to the safety of military vehicles, it is also necessary to mention the need for countermeasures in the event of a combat threat and the related protection of the crew. The vehicle's high level of features ensures optimum protection for the crew. These include firepower (the ability to hit the enemy with appropriate, effective firepower), ballistic and mine resistance (expressed by the quality of armour) [6, 7], traction characteristics (driving dynamics, overcoming terrain obstacles, handling) [8]. Only a comprehensive development of these features allows a satisfactory level of safety to be achieved. All disproportions, such as strong armouring with low movement dynamics, are undesirable and do not guarantee the safety of a military vehicle, especially armoured vehicles. The safety of military vehicles should be examined in a broad aspect, e.g.: ballistic resistance, ability to transport special equipment (including necessary military supplies, which can also be dangerous [9]), ability to overcome water obstacles, and the possibility to move through difficult terrain [10]. The quality of a military vehicle (especially a combat vehicle) is determined primarily by the main – essential characteristics, i.e.: firepower and armour, which in the sense of the chain of principles must be links, with the same resistance.

The quality of the vehicle can be generally described as meeting the requirements of the operator, or respective combat units. This applies not only to combat vehicles, but also to accompanying (logistics) vehicles. In the context of the above-mentioned, it is clear that safety and security aspects play a key role not only

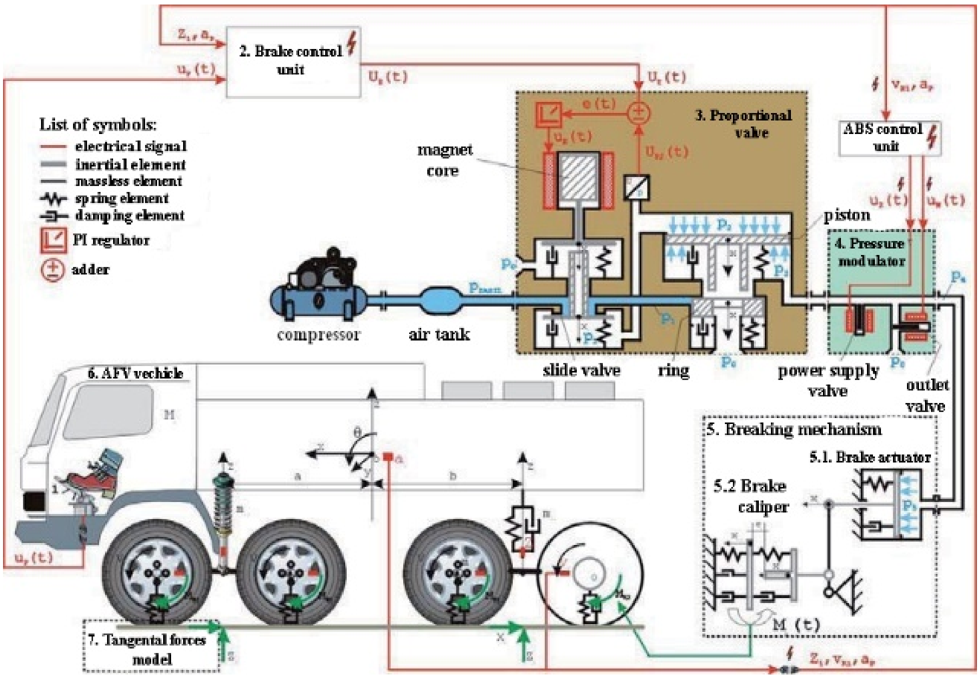


FIGURE 1. Simulation model – structure of main blocks.

in relation to the actions of the enemy, but also from the point of view of vehicle operation [11, 12], e.g. for logistics vehicles. Primarily, for the transport of dangerous goods (typically high-consumption supplies, e.g. ammunition, petrol, oil and lubricants), but also for others supplies (e.g. spare parts, building material), it is necessary to pay attention to the principles of cargo securing [13, 14], which in "combat" conditions show certain specificities [15, 16]. This is a more significant effect of shock and vibrations on the vehicle [17], cargo and driver, which in extreme cases can lead to a traffic accident. The wearing out of individual parts of the vehicle then has the effect of shortening its operability on the battlefield. The advantage is the use of modern technologies for these purposes, which allow the use of various sophisticated sensors [18, 19], which offer either the evaluation of risk data using appropriate methods [20] and the adoption of corrective measures, or a direct online overview of the vehicle, the cargo (securing), but also the driver, during transport [21].

Among the vehicles exposed to the destruction of sensitive circuits and systems, which are required to have a high level of the above-mentioned key characteristics, are armoured personnel carriers. The action of firing the mounted weapons can lead to malfunctioning of the braking system [22]. In addition, intensive and incorrect operation can lead to accelerated wear of working parts [23, 24]. For these reasons, it is necessary to carry out simulation tests of the effect of a malfunctioning braking system on the behaviour of the vehicle in curvilinear motion [25–27].

3. VEHICLE MODEL

A flat-planar simulation model of a four-axle vehicle with an integrated air braking system (Figure 1) was prepared for the test, which can be divided into seven sub-models based on their function:

(1.) control variable model,

(2.) brake control model,

(3.) proportional relay valve model (one for front and one for rear wheels),

(4.) ABS pressure modulator model together with the control unit (one for each of the four-wheel groups),

(5.) brake mechanism model (for each wheel),

(6.) vehicle model,

(7.) tangential forces model.

The vehicle model highlights those features that are considered to be particularly important in the event of a delayed movement caused by the sudden application of the braking system, in particular:

- the weight parameters of the vehicle, including the weight of the chassis of each axle,
- the mass moment of inertia of the wheels I_i and the moment of inertia of the vehicle body relative to its transverse axis (I_Y),
- the position of the vehicle's centre of gravity (a, b, h_W),
- physical parameters of the wheel axle suspension model ($k_{\mathrm{R}i}$, $c_{\mathrm{R}i}$),
- physical parameters of the model of radial elasticity of tyres ($k_{\mathrm{K}i}$, $c_{\mathrm{K}i}$).

The movement of the individual bodies of the model is described by equations for ten degrees of freedom (six for the body, one for the axles of the chassis and two degrees of freedom for the wheels rotating around

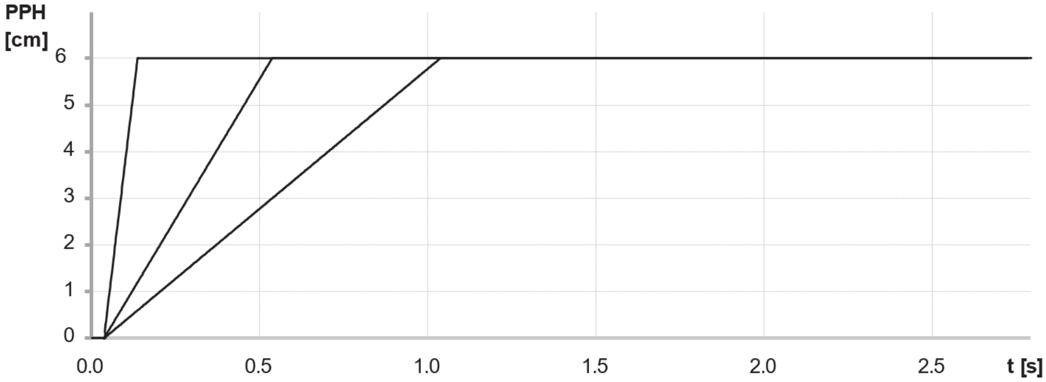


Figure 2. Example brake pedal pressure waveform (PPH) differentiated with respect to its rapid increase (0.2 s, 0.5 s, 1.0 s).

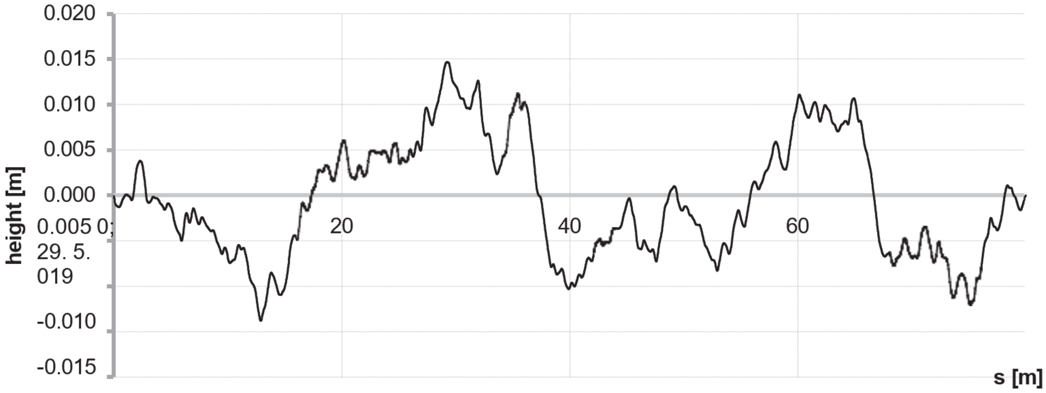


Figure 3. The course of the value of vertical road irregularity.

their axles). The input value for the vehicle model is the M_{Hi} value of the wheel friction moment of each driving axle. The output of the model is a set of physical values describing the kinematics (a_P – braking delay, v_{Ki} – wheel speed) and dynamics (Zi – forces of pressure of the wheels on the subgrade) of its movement.

The tangential force model provides information about the force values at the points of contact between the tyres and the substrate. The model uses the algorithm proposed by Dugoff, Fencher, and Segela. The necessary parameters required for the tangential force model were chosen according to the experimental data of the tyres used for the vehicles.

The control variable acting on the model is the brake pedal pressing waveform. An example dependency used for the initial simulation tests under intensive braking conditions can be seen in Figure 2.

An additional "external" controlling element acting on the model can be the course of vertical irregularities coming from the road (Figure 3).

The equations of motion of the vehicle model were recorded in three orthogonal, right-handed coordinate systems Oxyz, $\mathrm{O_1x_1y_1z_1}$, $\mathrm{O_2x_2y_2z_2}$. The basic equations governing the value of the dynamic vertical forces acting on the vehicle body include the equations for the vertical movement of the body with mechanical or hydropneumatic suspension. A description is given in the [27].

The model takes into account: the cushioning and damping properties of the hydropneumatic suspension. In the formulation of the mathematical equations of the hydropneumatic suspension element model, the diagram of which is shown in Figure 4, the following assumptions and simplifications were done:

- the viscosity, density, and temperature of the liquid are not subject to change during the passage of the process,
- the viscous friction forces of the piston in the cylinder are not taken into account due to their small value,
- the fluid is incompressible and the parts carrying the working fluid pressure are rigid and do not deform due to movement or changes in pressure,
- the fluid flow is continuous.

The mathematical description of the hydropneumatic column model is based on mathematical equations including:

- equations describing the work of moving parts,
- equations of pressure loss of fluid flow through hydraulic parts,
- equations of instantaneous mass flow of a fluid (knot equations or circuit equations).

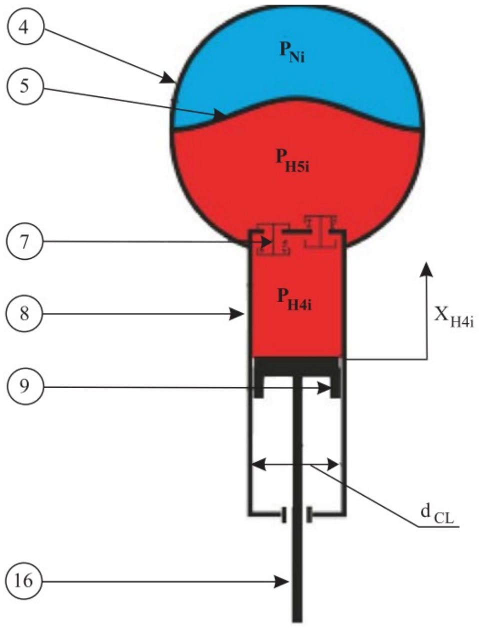
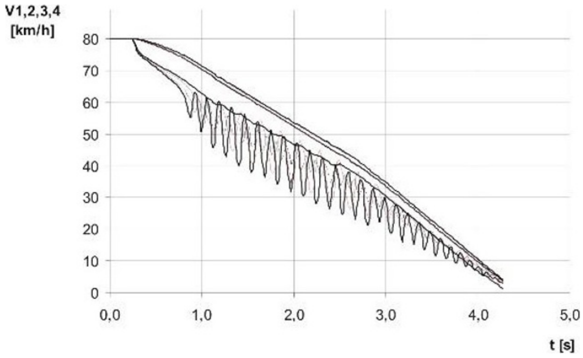


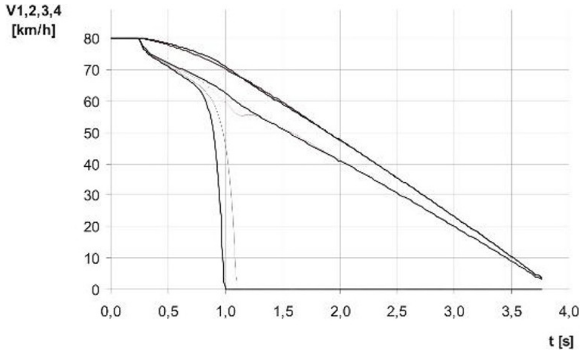
Figure 4. Calculation diagram of the hydropneumatic suspension column Designation: 4 – flexible pneumatic part, 5 – membrane, 7 – damping element, 8 – hydraulic cylinder, 9 – piston, 16 – piston rod.

4. Variants of simulation calculations

The developed vehicle model with hydropneumatic suspension and EBS/ABS braking system allows simulation calculations to be performed according to different model configurations. The tests can also determine the effect of selected design changes on the vehicle's behaviour in motion: start-up speed, suspension type, braking time, suspension type, air pressure in the air system air chamber, ABS configuration, and number of braked wheels [28]. In order to obtain information on the behaviour of the armoured vehicle in curvilinear motion, a simulation test was carried out according to the established test – emergency braking in curvilinear motion. The test simulated the emergency braking process from an initial speed of $80\,\mathrm{km\,h^{-1}}$ to a stop on the following surfaces: concrete ($\mu_0 = 0.9$), wet asphalt ($\mu_0 = 0.5$), and ice ($\mu_0 = 0.2$). The braking process was considered for a braking system with ABS on and off and for two states of braking system sufficiency: sufficient, i.e. 8 braked wheels, partially sufficient, i.e. 4 rear braked wheels (braking system of the wheels of the first and second driving axle is insufficient, braking system of the wheels of the third and fourth driving axle is sufficient). The nominal values of the model parameters correspond to the Rosomak vehicle. In addition, a variable range of design changes is possible, which includes the following vehicle parameters: weight, mass moments of inertia of the body-body, and changing the position of the centre of gravity.



(a).



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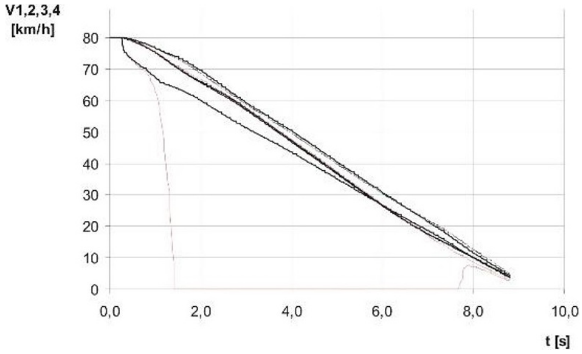


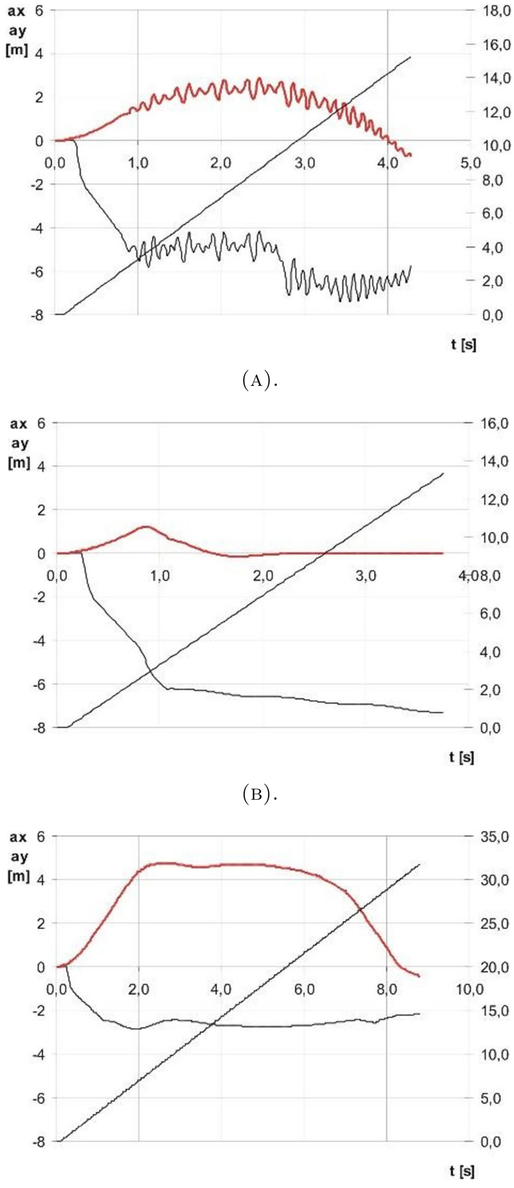
(c).

Figure 5. Time characteristics of the linear velocity on the wheels of each axle during braking on a curved road – concrete surface.

5. Test results

5.1. Dry surface tests

The results of the tests were presented in graphs representing the temporal characteristics of the parameter changes during the manoeuvre. The surface was characterised by a coefficient of adhesion of 0.9. Figure 5 shows the time characteristics of the linear wheel speed on each of the 4 axles of the vehicle for three variants: a sufficient braking system and ABS on (Figure 5a); a sufficient braking system and ABS switched off (Figure 5b); insufficient brake system and ABS off (Figure 5c). For the same variants, respectively, Figure 6 shows the time characteristics of the longitudinal acceleration and the lateral acceleration; Figure 7 shows the time characteristics of the vertical reactions from the subgrade; Figure 8 shows the time



(a).

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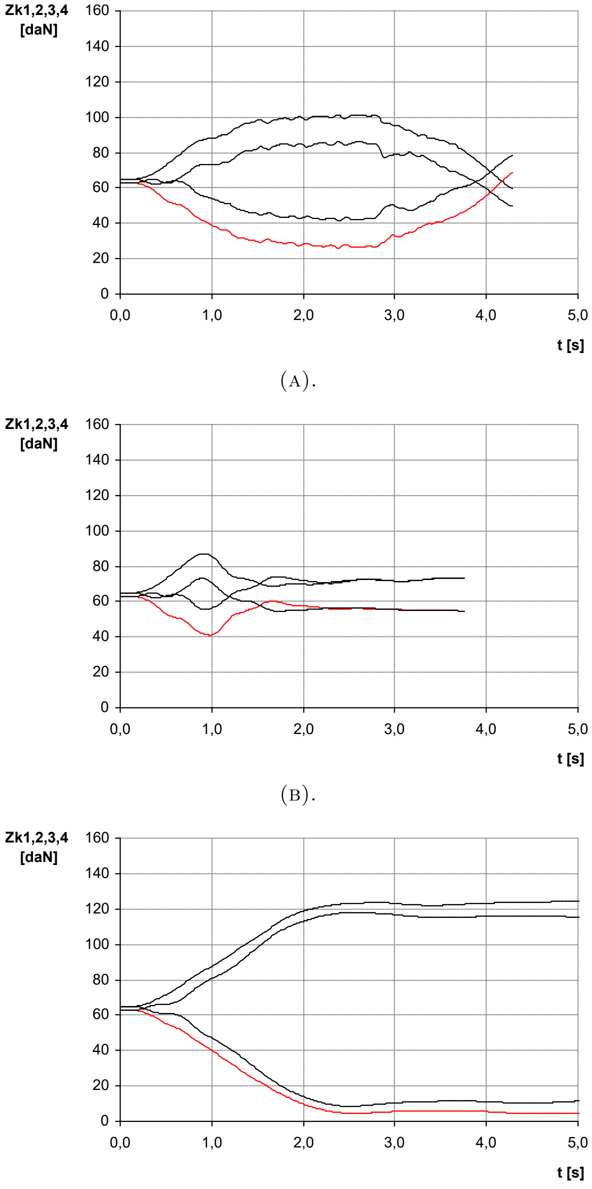
Figure 6. Temporal characteristics of longitudinal acceleration and lateral acceleration at the centre of gravity of the vehicle during braking on a curved road – concrete surface.



(a).

(b).

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Figure 7. Time characteristics of vertical reactions from the subgrade during braking on a curved road – concrete surface.

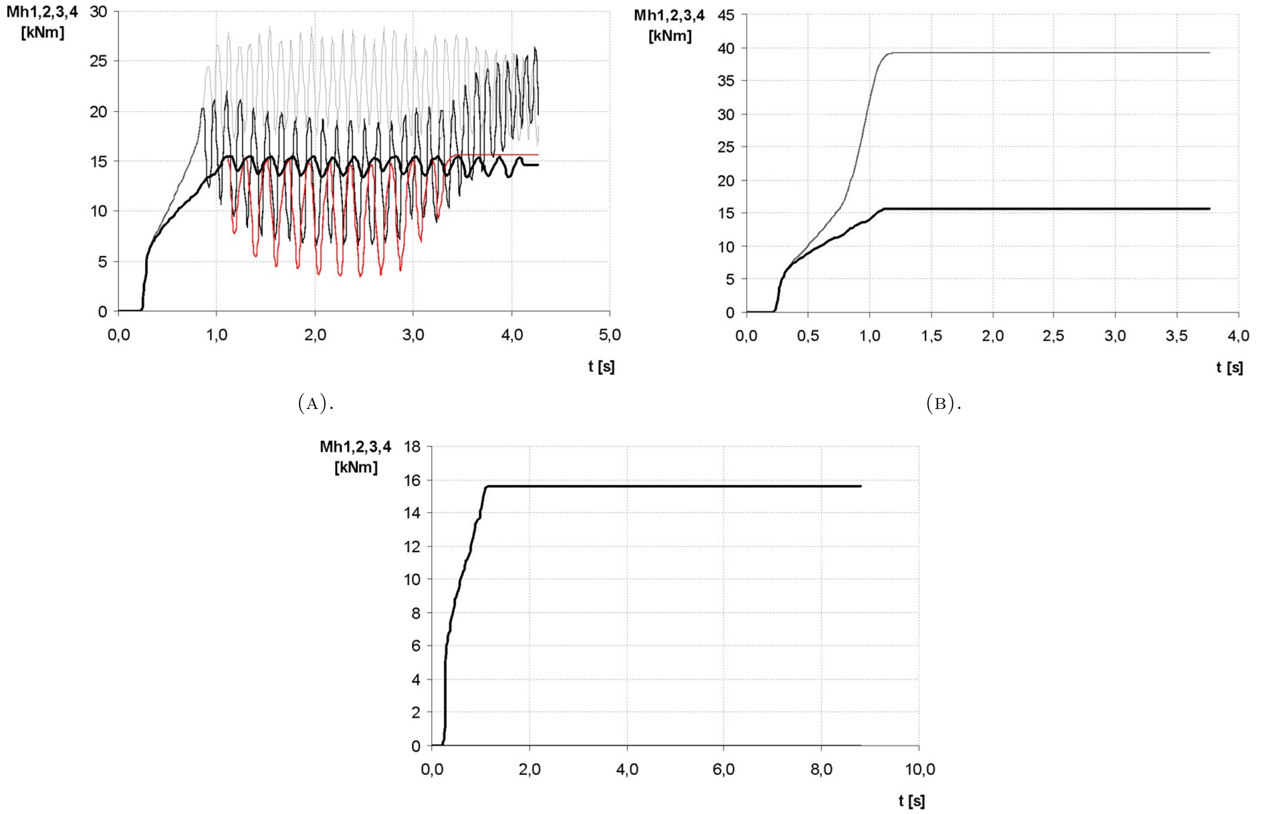
characteristics of the braking torque on the wheels during braking.

The test results for the concrete surface allow to conclude that the highest braking intensity is characteristic for variant 2 (sufficient brakes, without ABS). The highest deceleration and at the same time the highest braking torque was generated. The wheels on axles 3 and 4 lock up. However, only with variant 1 does the vehicle maintain stability. In variant 2, the vehicle does not continue in the specified direction of travel on the curve, it goes into a delayed straight-line motion. In variant 3, where only the brakes on axles 3 and 4 are applied, the wheels are lightened on the inside. The vehicle is positioned between the wheel chafing from the subgrade, reinforcing the road.

5.2. Wet surface tests

In the next stage of the tests, a wet surface is simulated by modifying the coefficient of adhesion. Figure 9 shows the time characteristics of the linear wheel speed on each of the 4 axles of the vehicle for the three variants, respectively. For the identical conditions, respectively, the time characteristics of longitudinal acceleration and lateral acceleration are plotted in Figure 10; Figure 11 shows the time characteristics of the vertical reactions from the subgrade; Figure 12 shows the time characteristics of the braking torque on the wheels during braking.

Tests on wet surfaces made the vehicle's tendency to stick to dry surfaces convex. Variant 2 is the fastest way to stop the vehicle. In this case, the effect of the highest value of the braking model is to lock the



(a).

(b).

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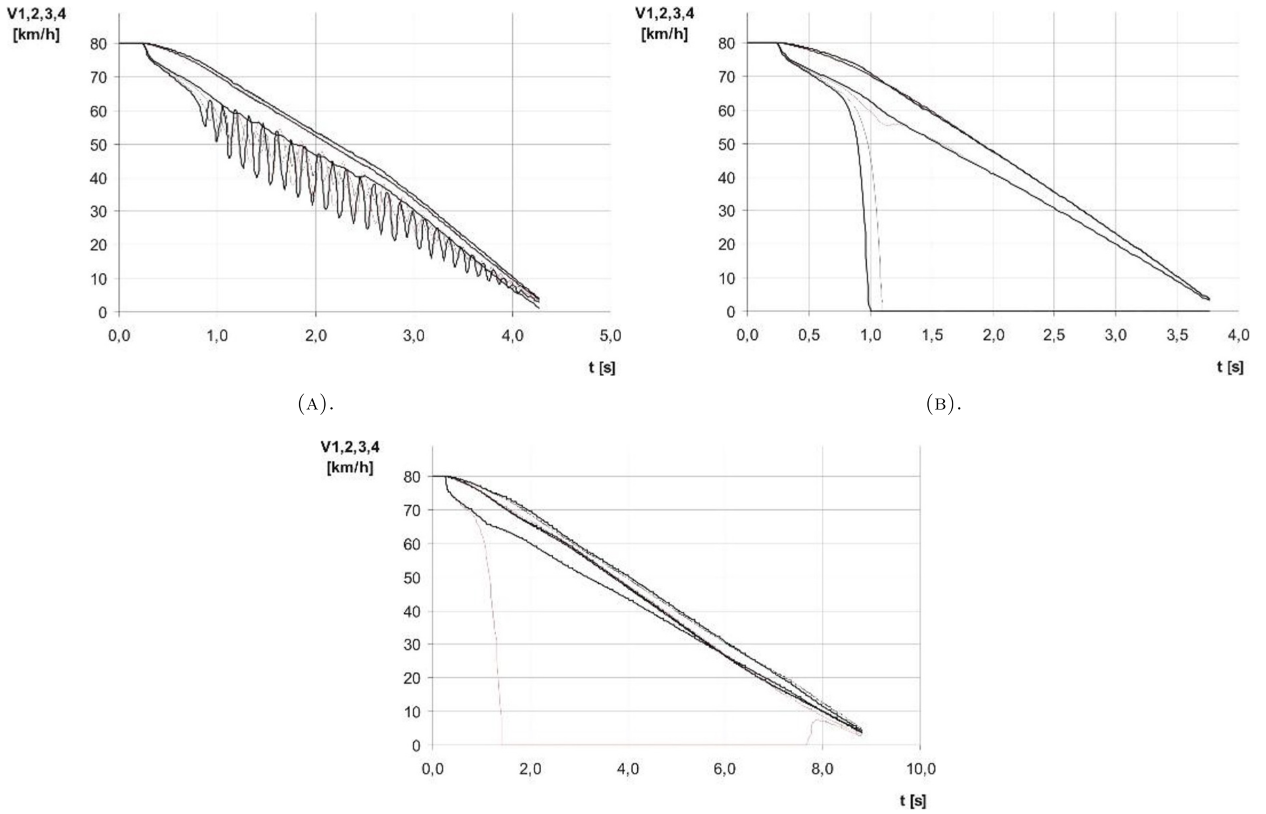
Figure 8. Temporal characteristics of the braking torque on the wheels during braking on a curved road – concrete surface.



(a).

(b).

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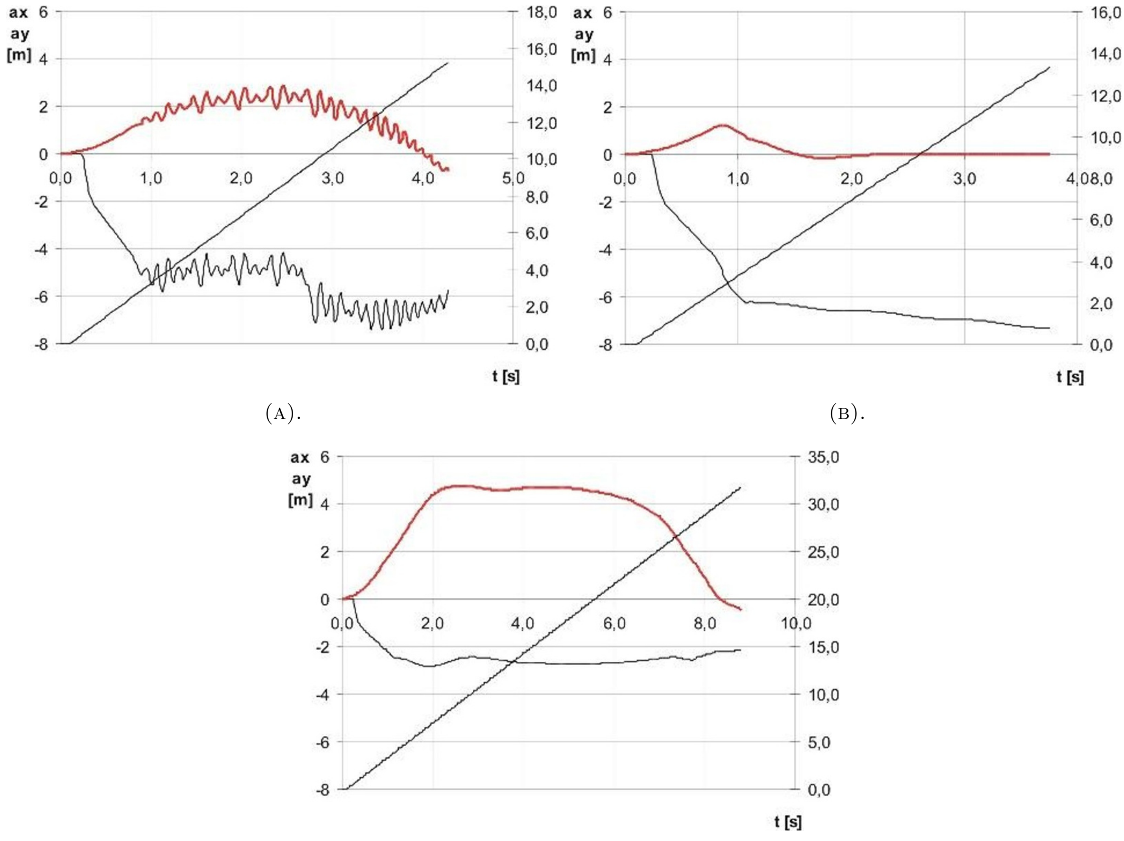
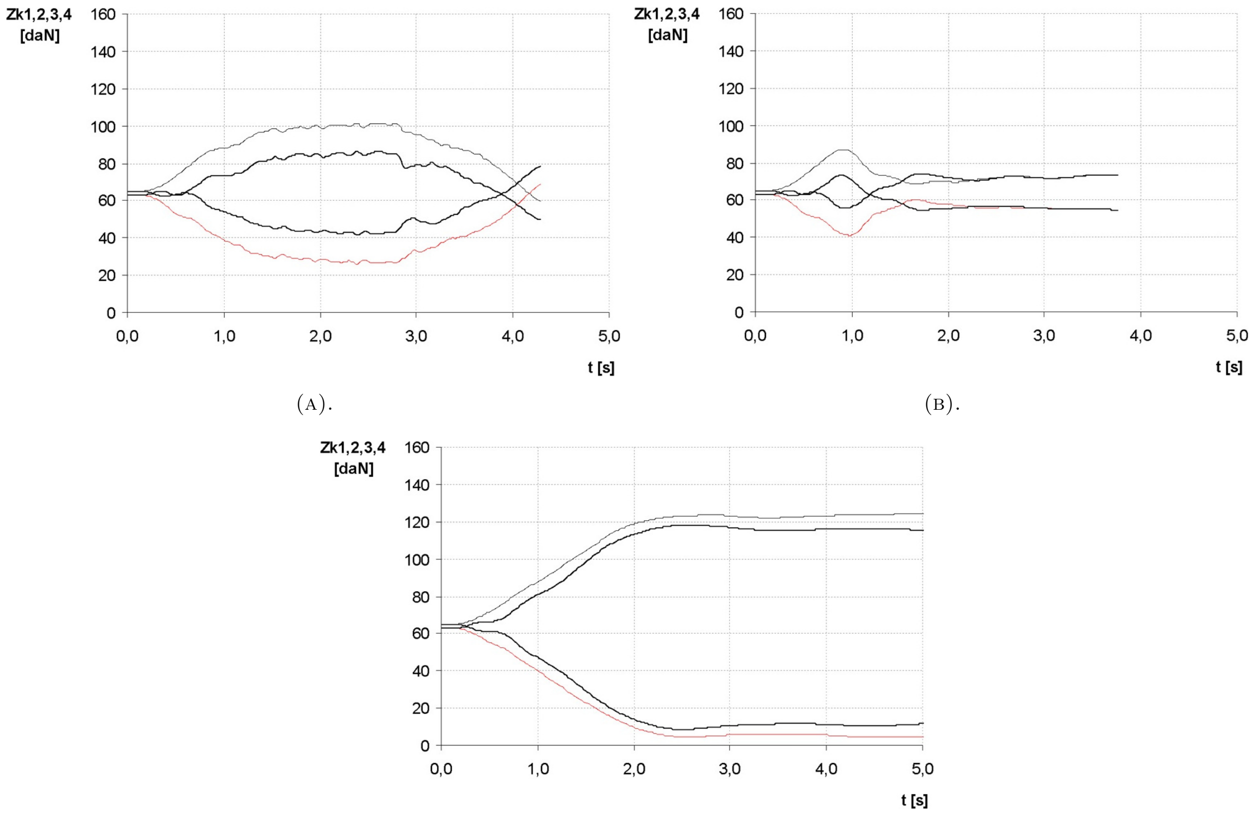
Figure 9. Time characteristics of the linear velocity on the wheels of each axle during braking on a curved road – wet surface.



(a). (b).

(c).

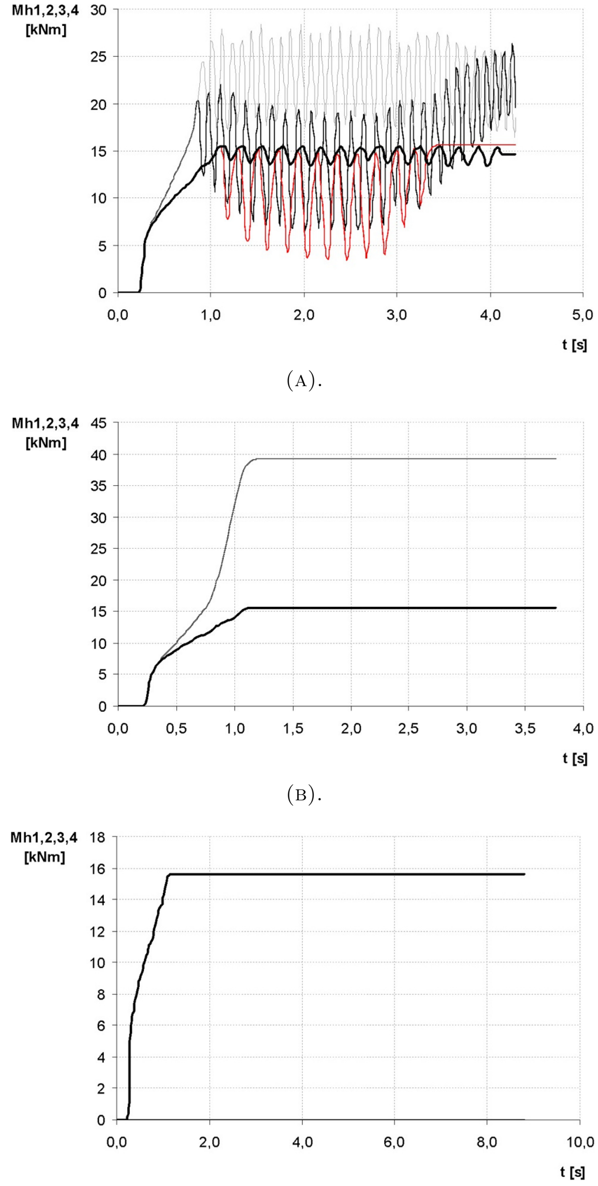
Figure 10. Temporal characteristics of longitudinal acceleration and lateral acceleration at the centre of gravity of the vehicle during braking on a curved road – wet surface.



(a). (b).

(c).

Figure 11. Time characteristics of vertical reactions from the subgrade during braking on a curved road – wet surface.

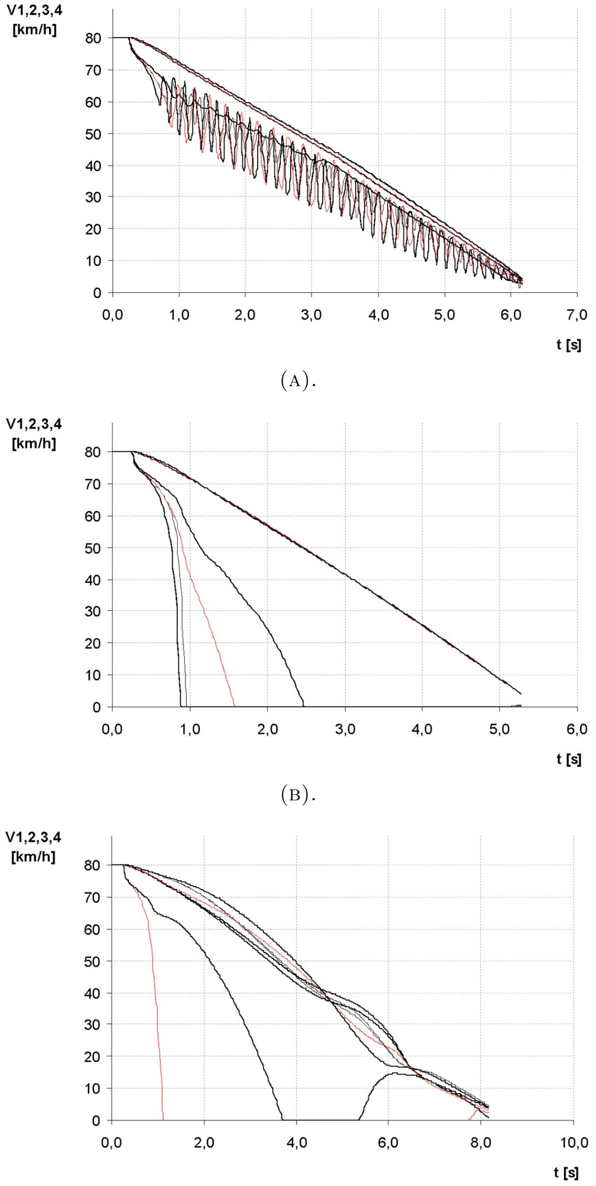


(a).

(b).

(c).

Figure 12. Temporal characteristics of the braking torque on the wheels during braking on a curved road – wet surface.



(a).

(b).

(c).

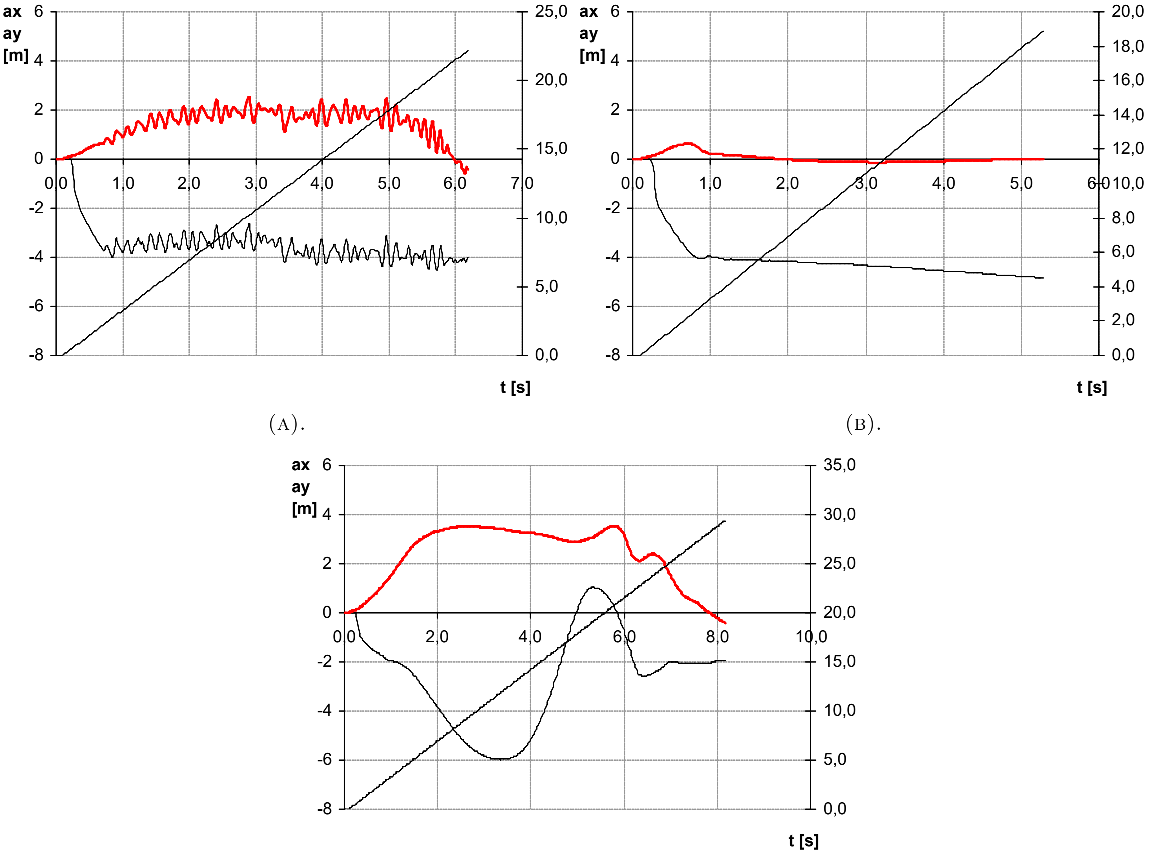
Figure 13. Time characteristics of the linear velocity on the wheels of each axle during braking on a curved road – icy surface.

wheels of axles 2, 3 and 4. As a result of wheel lockup, the vehicle starts to move in a straight line, away from the steered wheels. In variant 3, the braking intensity is the lowest. In addition to the low braking torque, the wheels of the last axle lock up. The vehicle goes into a yaw, shortening the travel distance, which leads to a change in the direction of lateral acceleration and a significant difference in the reactions from the ground between the sides of the vehicle.

5.3. Tests on icy surfaces

Reducing the coefficient of adhesion to 0.2 allowed simulation tests equivalent to icy surface conditions. Figure 13 shows the time characteristics of the linear wheel speed on each of the 4 axles of the vehicle for the three variants, respectively. For identical variants, respectively, Figure 14 shows the time characteristics of the longitudinal acceleration and the lateral acceleration; Figure 15 shows the time characteristics of the vertical reactions from the subgrade; Figure 16 shows the time characteristics of the braking torque on the wheels during braking.

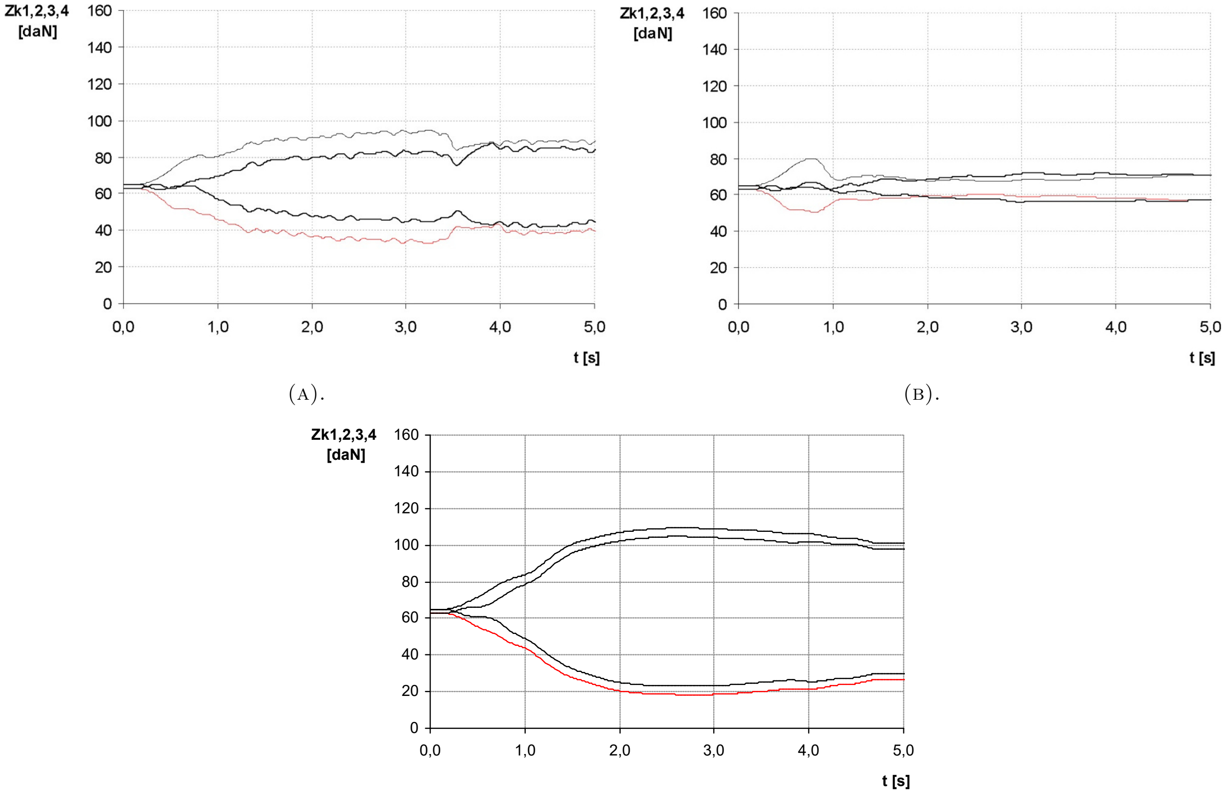
The movement on icy surfaces resulted in high ABS activity. Only in this variant did the vehicle maintain a curvy driving path. In variant 2, the wheels of axles 2, 3 and 4 locked up, the vehicle lost stability from the start and moved in a straight-line motion, as evidenced by the transverse acceleration value of the body – vehicle body, equal to 0. In the case of an unsafe – damaged braking system, after 3 seconds of movement, sideways skidding and uncontrollable wheel slipping occurs.



(a). (b).

(c).

Figure 14. Temporal characteristics of longitudinal acceleration and lateral acceleration at the centre of gravity of the vehicle during braking on a curved road – icy surface.



(a). (b).

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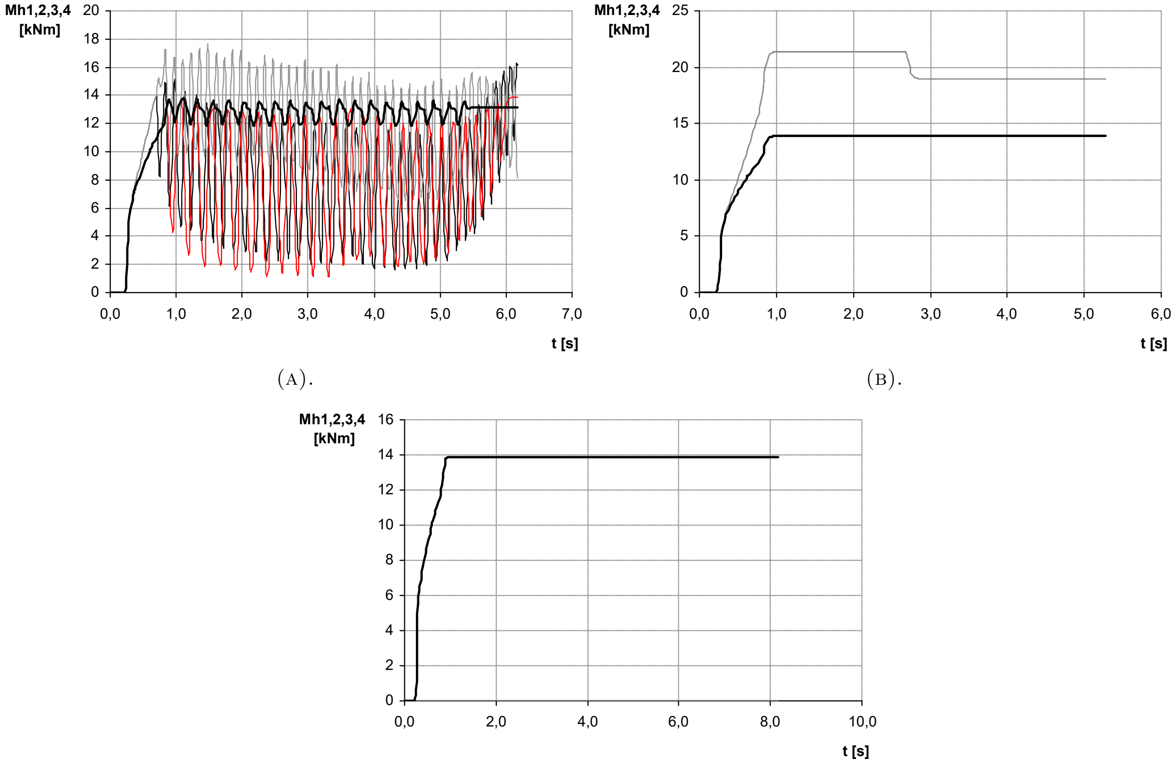
Figure 15. Time characteristics of vertical reactions from the subgrade during braking on a curved road – icy surface.



(A). (B).

(C).

FIGURE 16. Temporal characteristics of the braking torque on the wheels during braking on a curved road – icy surface.

6. CONCLUSION

During emergency braking, for a set of data adequate for a Rosomak class vehicle, it can be observed that wheel locking and the capability of the braking system affect the mobility of the vehicle. In this case, it is the ability to stop the vehicle on a specified curved path of travel. This can be important for obstacle avoidance and dynamic driving in combat situations. The role of a sufficient braking system becomes more important as the coefficient of adhesion decreases. Wheel lock in curving motion results in an increased tendency to go into straight-line driving or sideways skidding.

The results of the simulation tests can be used as a basis for decisions on the use of ABS, the control of its modulator, or the selection of an inter-axle brake force corrector. On the basis of the results, it is possible to prepare training programmes (scenarios) for drivers of special vehicles if their training does not include parts of driving techniques in critical situations.

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