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SIMULATION OF A MOTOR VEHICLE BRAKING ON A RANDOMLY UNEVEN ROAD

Symulacja ruchu samochodu hamującego na losowo nierównej drodze

Abstract: *In this paper a simulation of a vehicle's braking maneuver in various adopted road conditions has been presented. The aim of this paper was to answer the question whether the random irregularities of a road surface could limit the distance covered by the braking vehicle. At the same time it seems necessary to consider the damaging effect of the road irregularities along with the lack of comfort for both the driver and the passengers. The adopted maneuver of braking started at the initial speed of 100 km/h each time and lasted 10 s. The irregularities adopted for the simulation had three different amplitudes which enabled analysis of vehicle's deceleration on variously uneven road. Almost different profiles were assumed for the left and the right wheels of the vehicle's model as well as both the dry and the icy surface on the road.*

Keywords: vehicle's braking, random road irregularities, computer simulation

Streszczenie*: W artykule przedstawiono symulację manewru hamowania pojazdu w różnych przyjętych warunkach drogowych. Celem artykułu była odpowiedź na pytanie, czy losowe nierówności nawierzchni drogi mogą skrócić drogę* proces hamowania pojazdu. *Jednocześnie konieczne wydaje się uwzględnienie szkodliwego wpływu nierówności drogowych oraz braku komfortu zarówno dla kierowcy, jak i pasażerów. Przyjęty manewr hamowania rozpoczynał się każdorazowo przy prędkości początkowej 100 km/h i trwał 10 s. Przyjęte do symulacji nierówności drogi miały trzy różne amplitudy, co pozwoliło na analizę wytracania prędkości pojazdu na drogach o różnym stopniu nierówności. Założono prawie różne profile dla lewego i prawego koła modelu pojazdu oraz zarówno suchą, jak i oblodzoną nawierzchnię jezdni.*

Słowa kluczowe: hamowanie samochodu, losowe nierówności drogi, symulacja komputerowa

1. Introduction

One of the most important maneuvers necessary to maintain safety in the road traffic is braking which enables collision prevention and adoption of the appropriate speed. The ability to brake efficiently is as essential as accelerating but at the same time it can cause some unpredicted effects, such as a drift or wheels lock, depending on the road conditions. The braking process should be properly controlled in order to avoid the unpredicted and often dangerous events which may occur in road traffic. If road conditions are difficult the braking vehicle can e.g. lose its stability or move in an uncontrolled way. Especially when there are random irregularities on the road the vehicles' safety in traffic may be affected as well as the ride comfort and the ease of maneuvering during braking. Multiple research on the road traffic safety connected to braking has so far been conducted, e.g. [1, 6, 13].

The aim of this paper is to present the certain considerations on the response of the presented vehicle's model to the disturbances originating from the road while braking from the initial speed of 100km/h. Three various amplitudes of the road irregularities have been adopted for the simulations. Also some secondary aspects of the effect of braking on the uneven road will be considered.

Research related to braking as one of the aspects of vehicles' dynamics has so far been discussed in many works, e.g. [8]. Especially the emergency braking has been outlined, e.g. [4, 14, 18] as well as the use of an anti-lock systems, as in [20]. One of the main problems in motor vehicles motion along any road are the phenomena occurring between the tires and the road surface. This has been discussed, e.g. in [2, 3, 5]. Braking efficiency has also been widely considered as a part of, e.g. [11, 12] and as an effect of warming up of the selected parts of a vehicle [16].

Of course, this paper requires also the look into a problem of the random irregularities on a road, which has also been analyzed from various points of view, e.g. [7, 9, 10, 15] as a factor having the greatest influence, e.g. on a vehicle's vibrations.

Research on other means of transport, regarding, for example, the ride comfort can be exemplified by, e.g. [17] where the rail vehicles have been taken into account. On the other hand research on various means of transport can be related to safety, economy and ecology at the same time.

2. Assumptions for the simulations

For the presented analyzes a double seater vehicle's model was used (fig. 1) as in some previous works by the author, e.g. [19]. Location of the loading masses was adopted in accordance with [19] as well as the resulting increase of the mass of the vehicle's body which, along with the resulting mass-inertia parameters has been presented in table 1. Also following [19] the center of mass of the vehicle before and after the loading has been determined versus the so-called ‘origo’ point (fig. 1) as well as the moments of inertia and deviation (in relation to the axes intersecting the ‘origo’).

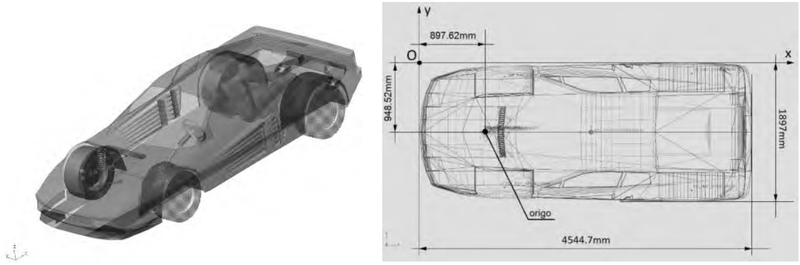


Fig. 1. Location of the ‘origo’ point and the basic dimensions of the vehicle [19]

From the previous experiences it seems more convenient to determine the location of the center of mass and the moments of inertia of a vehicle’s model in relation to the axis system located outside the vehicle but moving with it rather than any other systems which could cause difficulties and uncertainty of the calculations. Here the coordinates presented in table 1 were obtained with the use of the ‘origo’ point which is the origin of a coordinate system located on a road surface and moving with the vehicle at the same time (fig. 1). However the main assumptions related to the mass – inertia parameters did not change when comparing with [19], because the adopted maneuver was aimed to be simulated for the same vehicle loading.

Table 1

Mass – inertia parameters of the unladen and laden vehicle’s model used in the simulations [19]

	unladen vehicle		laden vehicle	
	vehicle’s body	whole vehicle	vehicle’s body	whole vehicle
mass	995 kg	1528 kg	1153 kg	1686 kg
center of mass location relative to the ‘origo’ point	xc=1.5 m, yc=0, zc=0.45 m	xc=1.75 m, yc=-0.0014 m, zc=0.43 m	xc=1.508 m, yc=0.012 m, zc=0.452 m	xc=1.73 m, yc=-0.007 m, zc=0.435 m
moment of inertia (Ix)	401 kg·m^2	583 kg·m^2	436 kg·m^2	618 kg·m^2
moment of inertia (Iy)	2940 kg·m^2	6129 kg·m^2	3361 kg·m^2	6550 kg·m^2
moment of inertia (Iz)	2838 kg·m^2	6022 kg·m^2	3225 kg·m^2	6409 kg·m^2
moment of deviation (Ixy)	0	-1.9 kg·m^2	2.15 kg·m^2	1.95 kg·m^2
moment of deviation (Izx)	671 kg·m^2	1160 kg·m^2	787 kg·m^2	1276 kg·m^2
moment of deviation (Iyz)	0	-1.3 kg·m^2	0.64 kg·m^2	0.51 kg·m^2

The vehicle’s model used here was equipped with the FTIRE tire models as in [19] in order to enable motion on a randomly uneven road surface. Other assumptions regarded a partial nonlinearity of the vehicle's suspension, specifically the dampers as, e.g. in [6]. The remaining assumptions agreed with those form [19] as this paper is a continuity of a wider scope research.

The simulations have been performed with the use of MSC Adams/Car for some specified road conditions presented in table 2 with the initial speed at the beginning of the braking adopted at 100 km/h regardless the road conditions (dry or icy surface), the amplitudes of the random irregularities (*intensity*) and the almost different road profiles for the left and the right wheels ($cor_{rl} = 0.2$). The letter 'i' in the name of a specific configuration means the motion of a vehicle on an icy road as in [19].

Table 2

Configurations adopted for the vehicle's braking maneuver [based on 19]

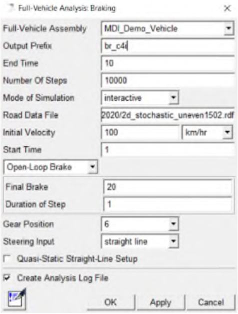
	road		intensity	corrl	initial V [km/h]
configuration 1	flat	dry	-	-	100
configuration 1i	flat	icy	-	-	100
configuration 2	uneven	dry	0.5	0.2	100
configuration 2i	uneven	icy	0.5	0.2	100
configuration 3	uneven	dry	1.0	0.2	100
configuration 3i	uneven	icy	1.0	0.2	100
configuration 4	uneven	dry	1.5	0.2	100
configuration 4i	uneven	icy	1.5	0.2	100

From table 2 it is obvious that there were 8 simulations of the same vehicle for different conditions of motion. Duration of each simulation was adopted at 10 s which did not guarantee a full stop but only a significant speed reduction which is essential, e.g. in collision avoidance.

As in [19] two parameters (*intensity* and cor_{rl}) played a decisive role in establishing the conditions of motion from the point of view of a road. To remind what was said in [19] the *intensity* specifies the amplitudes of the irregularities in a random profile of a road whereas the cor_{rl} specifies the whether the profiles of the right and the left wheels are almost similar or almost different.

In the given case three values of the intensity have been adopted: 0.5, 1 and 1.5. Assuming that the wheels remained in contact with the road during each simulation the amplitudes reflecting the adopted values of intensity were presented in [19]. Also for the presented case the cor_{rl} has been set to 0.2 which means the profiles for the left and the right wheels were almost different making the maneuver more realistic. The cor_{rl} coefficient in Adams/Car means a correlation (similarity) of the road profile for the left and the right wheels, i.e. if it is close to 1 the shape of the irregularities on both sides is the same and if it is 0 then this shape differs completely. The value of this correlation coefficient varies between 0 and 1. Almost different means that only some minor parts of a shape of the road may be the same for both sides of the wheels but in case of the irregularities they should vary noticeably. This has been analyzed, e.g. in [6].

In fig. 2 the initial setting for each simulation have been presented. Except for the initial velocity and duration both the 6th gear and the straight line steering was adopted as well as the final brake set at 20 which corresponds to the pressure applied to the braking pedal, so it is not the direct force applied to the brakes, because the pedals in various models can have different areas.



Full-Vehicle Assembly	MDI_Demo_Vehicle
Output Prefix	br_c4i
End Time	10
Number Of Steps	10000
Mode of Simulation	interactive
Road Data File	2020/2d_stochastic_uneven1502.rdf
Initial Velocity	100 km/hr
Start Time	1
Open-Loop Brake	
Final Brake	20
Duration of Step	1
Gear Position	6
Steering Input	straight line

☐ Quasi-Static Straight-Line Setup

☑ Create Analysis Log File

Fig. 2. Adoption of the straight line driver control [own research based on MSC Adams/Car]

3. Discussion on the selected results of the simulations

Since it was adopted that for the simulated maneuver the steering input was set for a straight line motion it seems fair to mention that one of the aims of this paper was to examine whether braking on an uneven road could cause the vehicle deviate in the lateral direction and if the irregularities can have an additional braking effect on the vehicle.

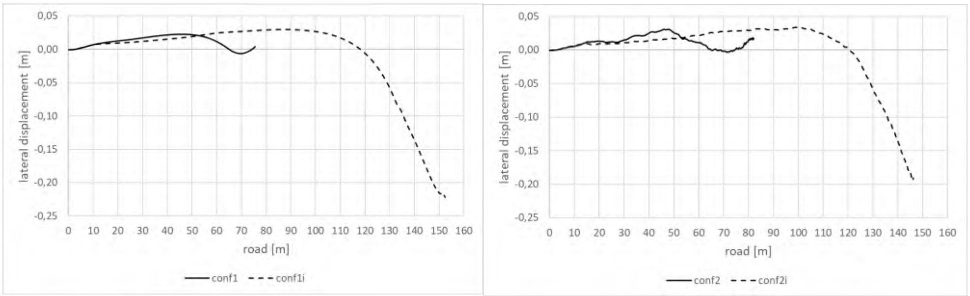


Fig. 3. Lateral displacement for the configurations 1, 1i, 2 and 2i

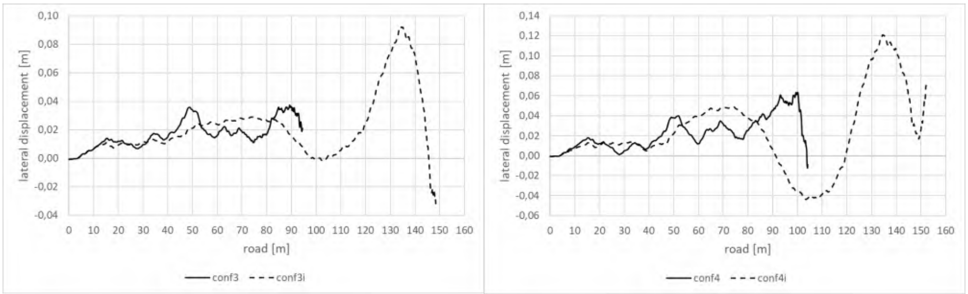


Fig. 4. Lateral displacement for the configurations 3, 3i, 4 and 4i

In figs. 3 and 4 the lateral displacement has been presented for all of the configurations presented in table 2.

As it could be expected the icy road caused the greater braking distance by about 70 – 80 m versus the dry road for the configurations 1, 1i, 2 and 2i and by about 55 m for the configurations 3, 3i, 4 and 4i. The lateral displacement was insignificant reaching as much as 0.2 m for the icy road (configurations 1, 1i, 2 and 2i) and 0.12 m for the configurations 3, 3i 4 and 4i for the icy road as well. This is undoubtedly due to the adopted straight line steering. The braking nature of road irregularities is not directly clear, especially in case of the dry road (configurations 1, 2, 3 and 4) because the higher amplitudes of the irregularities the longer the braking distance. This can be explained by the lack of full contact between the wheels and the road which is necessary for such an important maneuver as braking.

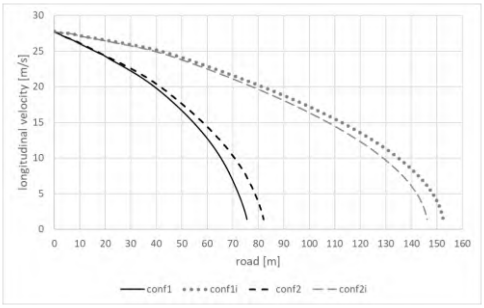


Fig. 5. Longitudinal velocity loss due to braking for the configurations 1, 1i, 2 and 2i

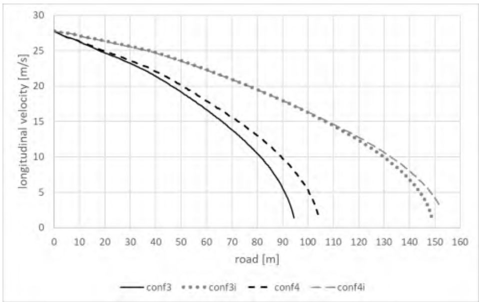


Fig. 6. Longitudinal velocity loss due to braking for the configurations 3, 3i, 4 and 4i

In figs. 5 and 6 the loss of the longitudinal velocity has been presented. This is also a proof that the icy road can lengthen the braking distance because the vehicle reached the same velocity after about 70 m greater distance for the configurations 1i and 2i (fig. 5) and about 50 m for the configurations 3i and 4i.

Moreover, the higher amplitudes of the irregularities made the braking distance even longer when comparing the configurations 1 and 2 (dry road, fig. 5) and shorter for the icy road (configurations 1i and 2i). This can be explained by the fact that the ires did not adhere to the road surface properly. As for fig. 6 the dependencies are the same as in fig. 5, except for the comparison of an uneven road with different amplitudes of the irregularities.

Further analysis is related to the potential lateral motion of the vehicle as an effect of a randomly irregular road as well as the vertical vibrations caused by these irregularities. In figs. 7 and 8 the changes in the lateral velocity along the covered distance have been presented.

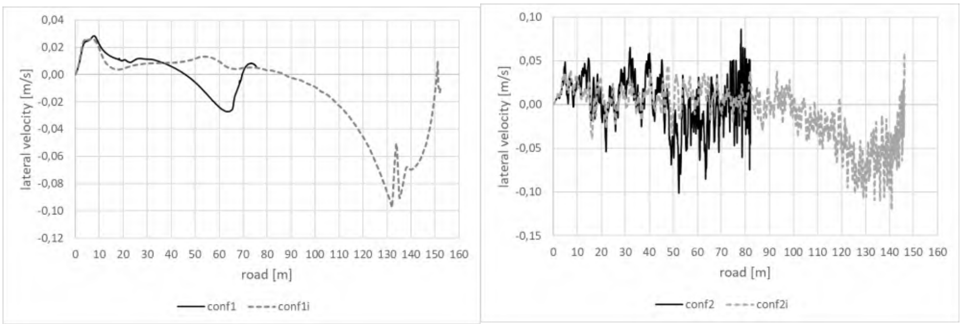


Fig. 7. Lateral velocity changes due to braking for the configurations 1, 1i, 2 and 2i

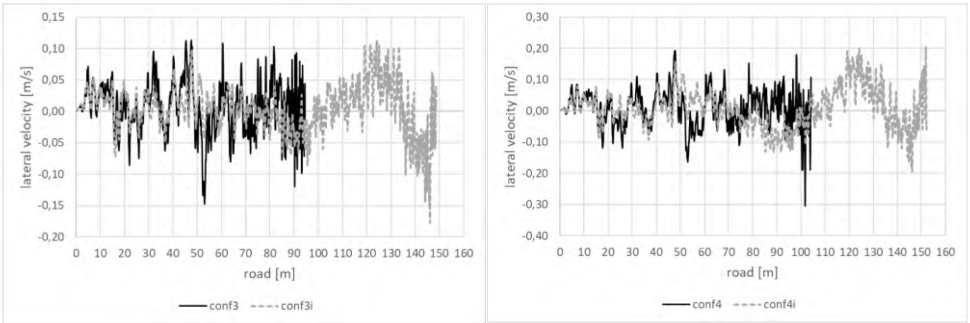


Fig. 8. Lateral velocity changes due to braking for the configurations 3 and 3i

It is clear that the velocity did not have great values each time but its changes were rapid, especially in case of the random irregularities on the road. It indicates that, despite the straightforward steering the random irregularities may have caused the vehicle to drift laterally due to both the uneven spread of mass and the poor quality of road conditions.

One of the problems of the vehicle's response to the external disturbances coming from the road is the vertical motion, particularly acceleration, which is especially important when considering both safety and ride comfort. In figs. 9 to 12 the vertical acceleration on each of the adopted road conditions has been presented. In case of a dry road, i.e. configurations 1 and 1i (fig. 9) the maximum value of this acceleration was up to about 16 m/s^2 and 19 m/s^2 respectively, but only at the beginning of the maneuver. Then, after about 10 or 20 m of the distance it decreased close to 0. On the more uneven road (configurations 2 and 2i, fig. 9) the initial value of the vertical acceleration was only a little higher than in case of a dry road but it did not decrease to almost 0. The changes of this parameter was more turbulent and reached up to ±5 m/s^2 along the whole distance covered by the braking vehicle. amounted up to 10 – 11 m/s^2.

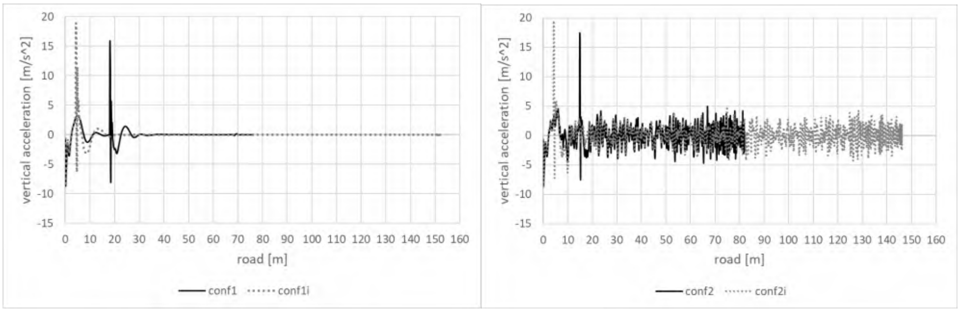


Fig. 9. Vertical acceleration due to braking for the configurations 1 and 1i

The same situation occurred in case of configurations 3 and 3i (fig. 10) as well as 4 and 4i (fig. 10, right part) with the main difference in the value of the acceleration reached after the first 10 – 20 m of the road. In case of configurations 3 and 3i the acceleration oscillated around 0 as in the previous case but changed between ±5 m/s^2 and ±7 m/s^2, once reaching up to ±10 m/s^2.

In case of configurations 4 and 4i the peak value of the acceleration, after the first 20 m was even ±12 m/s^2 and one can observe that it changed from ±7 m/s^2 to ±10 m/s^2. The higher the irregularities of the road the more turbulent the were the changes in the vertical acceleration which seems natural.

Moreover, the presented results also prove that the braking distance was shorter for a dry road than an icy one. Plus they show that the differences between the braking distance were smaller for the more difficult road conditions (higher amplitudes of the irregularities).

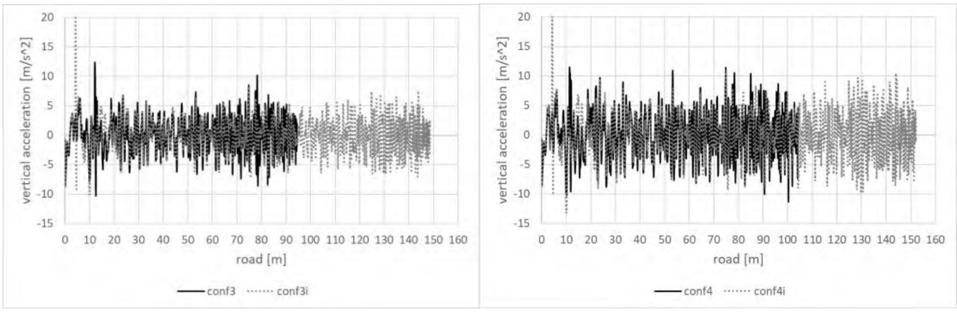


Fig. 10. Vertical acceleration due to braking for the configurations 3 and 3i

The values presented in figs. 9 to 12 also show that the braking maneuver may involve the increase of the vertical acceleration due to the fact, that the front axle is usually weighed down while the rear axle is relieved at the same time and the center of mass of the vehicle is usually moving up and down, especially when braking on a poor quality road.

4. Conclusions

From the presented results it can be observed that the random road irregularities may in some cases increase the vehicle’s braking distance and cause the lateral motion at the same time. Moreover, braking from the initial speed of 100 km/h may affect the technical condition of the vehicle’s suspension as the occurring vertical acceleration may amount above between 10 m/s^2.

Further research may be upgraded with the lack of straight line steering which, taking into account the random nature of the road unevenness may cause even greater deviations from the assumed direction of motion. However, such research seem reasonable as the non – destructive alternative to the field tests.

5. References

1. Agostinacchio M., Ciampa D., Olita S.: The vibrations induced by surface irregularities in road pavements – a Matlab® approach. European Transport Research Review, Vol. 6, 2014, DOI: 10.1007/s12544-013-0127-8.
2. Chen Ch., Jia Y., Wang Y., Shu M.: Non-linear velocity observer for vehicles with tyre-road friction estimation. International Journal of Systems Science, Vol. 49(7), 2018, DOI: 10.1080/00207721.2018.1454533.
3. Grakovski A., Pilipovecs A.: Dynamics of Interaction between the Road Surface and Vehicle's Wheel in Fibre-optic System for Automatic Weighing in Motion of Transport. Procedia Engineering, Vol. 178, 2017, DOI: 10.1016/j.proeng.2017.01.052.
4. Haus S.H., Sherony R., Gabler H.C.: Estimated benefit of automated emergency braking systems for vehicle–pedestrian crashes in the United States. Traffic Injury Prevention, Vol. 20, Sup. 1, 2019, DOI: 10.1080/15389588.2019.1602729.
5. Kabanovs A., Garmory A., Passmore M., Gaylard A.: Investigation into the dynamics of wheel spray released from a rotating tyre of a simplified vehicle model. Journal of Wind Engineering and Industrial Aerodynamics, Volume 184, January 2019, DOI: 10.1016/j.jweia.2018.11.024.
6. Kisilowski J., Zalewski J.: Modeling of Road Traffic Events. Springer, 2022, DOI: 10.1007/978-3-030-91398-4.
7. Levulyte L., Žuraulis V., Sokolovskij E.: The impact of road roughness on the duration of contact between a vehicle wheel and road surface. Transport, Vol. 29(4), 2014, DOI: 10.3846/16484142.2014.984330.
8. Meywerk M.: Vehicle dynamics, Wiley, 2015.
9. Múčka P.: Current approaches to quantify the longitudinal road roughness. International Journal of Pavement Engineering, Vol. 17, Iss. 8, 2016, DOI:10.1080/10298436.2015.1011782.
10. Múčka P.: International Roughness Index Thresholds Based on Whole-Body Vibration in Passenger Cars. Transportation Research Record Journal of the Transportation Research Board, 2675(3):1-16, 2020, DOI: 10.1177/0361198120960475.
11. Navin F., Macnabb M., Nicolletti C.: Vehicle traction experiments on snow and ice. SAE Technical Paper Series, no. 960652, 1996, DOI: 10.4271/960652.
12. Ning L., Liu Y., Tan S.: Experimental Research on Braking Feedback and Taxiing Feedback System of New Energy Vehicles. Applied Sciences, vol. 11(23), 2021, DOI: 10.3390/app112311093.
13. Sabri M., Fauza A.: Analysis of vehicle braking behaviour and distance stopping, IOP Conference Series: Materials Science and Engineering, no. 309(1):012020, DOI: 10.1088/1757-899X/309/1/012020.
14. Surblys V., Sokolovskij E.: Research of the Vehicle Brake Testing Efficiency. Procedia Engineering, Vol. 134, 2016, DOI: 10.1016/j.proeng.2016.01.067.

15. Surblys V., Žuraulis V., Sokolovskij E.: Estimation of road roughness from data of on-vehicle mounted sensors. Eksploatacja i Niezawodnosc – Maintenance and Reliability, Vol. 19 (3), 2017, DOI: 10.17531/ein.2017.3.7.
16. Synák F., Rievaj V., Kučera M., Šebök M., Skrúcaný T.: Effect of repeated vehicle braking on the warming of selected parts of the vehicle. Scientific Journal of Silesian University of Technology, Series Transport, Vol. 107, 2020, DOI: 10.20858/sjsutst.2020.107.14.
17. Wawryszczuk R., Kardas-Cinal E.: Analysis of ride comfort in selected types of rail vehicles. Journal of KONBiN, Vol. 51, Iss. 4, 2021, DOI: 10.2478/jok-2021-0049.
18. Yang W., Liu J., Zhou K., Zhang Z., Qu X.: An Automatic Emergency Braking Model considering Driver’s Intention Recognition of the Front Vehicle. Journal of Advanced Transportation, vol. 2020, DOI: 10.1155/2020/5172305.
19. Zalewski J.: Simulation of a motor vehicle momentarily accelerating in various road conditions. Journal of KONBiN, Vol. 51, Iss. 1, 2021, DOI: 10.2478/jok-2021-0010.
20. Zhao J., Zhang J., Zhu B.: Development and verification of the tire/road friction estimation algorithm for antilock braking system. Mathematical Problems in Engineering no. 786492, 2014, DOI: 10.1155/2014/786492.