STEERING STABILITY OF A BUS POWERED BY NATURAL GAS WHILE BRAKING

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Abstract: The use of natural gas as bus propellant presupposes the application of a driving unit adjusted to the use of natural gas in addition to the application of a corresponding gas facility. The first part of the paper describes the distinguishing features related to the storage of compressed natural gas tanks as the main carriers of additional mass due to the use of this energy substance for the propulsion of buses, as well as their effect on the structural features of vehicles. The second part of the paper covers the formulation and analysis of differential equations in terms of the steering system's stability, and the equations depict the motion of the natural gas bus with its structural features, according to the defined models for instances of bus braking with locked front, rear and all wheels.

Key words: natural gas, CNG bus, steering stability.

1. Introduction

The stability of a motor vehicle generally implies its ability to move on a desired trajectory under different conditions of operation without sliding (skidding) of one or more wheels of any axle (driven or dead) and without the vehicle overturn around its longitudinal or transverse axis (Dedović, 2004; Lenasi et al., 1995; Janković and Todorović, 1990).

The steering stability is singled out as a particular type of stability during the vehicle's motion and it is covered by the preceding definition (Simić, 1979; Mitschke, 2004; Rajamani, 2006). The distinctiveness of this concept is that it takes into account the kinematics of the steering system in addition to the effect of structural features on "stable motion" of the vehicle.

It is considered that the vehicle has steady steering if under the impact of external unbalanced forces the initial amplitudes of oscillation around the desired course of motion are decreased in a very short space of time, returning the vehicle to its original motion (Dedović, 1998). In this case, for the set conditions of motion, "disturbed motion" slightly differs in the course of time from undisturbed motion.

In the case of unstable steering the initial oscillation amplitudes increase over time, the vehicle deviates from its desired path, which leads to the driver not being able to maintain the motion along the desired trajectory or he manages to do so with considerable effort. In accordance with the above considerations, disturbed motion increasingly differs in the course of time from undisturbed motion.

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Disruption entails effects brought about by: different road phenomena (uneven spots, transverse and longitudinal gradient, etc.), interaction between the vehicle and road along which the vehicle moves (tangential and lateral reactions, etc.), inertial and aerodynamic effects (centrifugal force, flurry of wind, etc.).

Mathematically, the stated problems are best described by the Lyapunov definition. The formulation is based on the assumption that at a specific point in time unbalanced forces act on the vehicle, upsetting the balance of the parameters which depict the vehicle's motion along the desired trajectory, Eq. (1) and Eq. (2):

$$X(t_o) = X_o + \Delta X \quad (1)$$

$$Y(t_o) = Y_o + \Delta Y \quad (2)$$

where:

ΔX and ΔY are the values of the rate of change of the parameters at the moment exerted by unbalanced forces.

The vehicle's motion will be stable if the motion parameters ($Y(t_o)$ and $X(t_o)$) after little deviation stay close to the preceding values (Y_o) and remain as such in the subsequent course of time (Δt_{min} za $\Delta X \to 0$) (Ćućuz and Rusov, 1973; Janković, 1996). When the motion is unstable, the parameters which describe it after little deviation are not close to the initial values due to the rate of change in the course of time.

Bearing in mind the points mentioned above, we have carried out the analysis into the stability of steering the bus powered by compressed natural gas and the bus powered by diesel fuel i.e. the goal of this paper is to determine, from the perspective of steering stability, the extent to which the gas facility affects the driver's behaviour when braking in three typical cases – front wheels locked, rear wheels locked and all wheels locked.

The first part analyses the position of the gas facility within the bus and its effect on the vehicle's structural features.

The second part of the paper covers the formulation and analysis of differential equations which describe the motion of the gas powered bus with its structural features according to defined models for the cases of vehicle motion while braking, with some wheels being locked.

2. Position of a Gas Facility in a Bus

The use of natural gas as bus propellant presupposes the application of a driving unit adjusted to the use of natural gas in addition to the application of a corresponding gas facility. The number of elements of the gas facility and their functional properties largely depend on conceptual and structural design of an engine and the solution for gas storage within a bus.

Regardless of the type of a driving unit, the gas facility consists of and always includes the following elements: tundish system, gas line, stop valves, electromagnetic valves, pressure regulators, dispenser, impeller, control and measuring equipment, special elements that depend on the type of engine and vehicle, tank and tank battery.

The storage of the gas facility has to be carefully planned considering the natural gas properties, the need to ensure corresponding vehicle performances while corresponding conditions which affect functionality and safety have to be met as well. Out of the entire gas facility, structural features of the bus are mostly affected by gas tanks, while the volume of the remaining gas facilities (tundish system, pipes, dispenser-mixer, and others) is negligible against the volume of the tank so that its influence is disregarded.

CNG tanks can be installed in two places within the bus, on the roof or just under the floor. The position depends on the type of bus i.e. its corresponding structural and functional characteristics. The main factors (in addition to safety requirements) which affect the position of the tank are: the location of the driving unit and power transmission system; floor height and the overall height of bus; the presence and size of the trunk compartment.

In the case of urban buses CNG tanks can be installed under the floor if the chassis is not low-floored and if the engine is located at the rear overhang. With low-floor urban buses, considering the platform height (320-400mm), the only storage place is the reinforced roof.

Suburban and intercity buses meet the demands related to the storage of a tank under the floor, in terms of platform height (>950mm), if the engine is located at the rear. The problem with intercity buses in this case is caused by the necessary presence of a trunk compartment so that the gas is exclusively situated on the roof of these buses.

Tourist buses have 500 to 600-litre diesel fuel tanks, which, depending on the conditions of operation and manner of steering, provide them with the autonomy of around 1000 kilometres (Glumac et al., 2002). In the case of compressed natural gas propulsion, the provision of greater amount of fuel is necessary for the same turning radius, with regard to urban, suburban and intercity buses. In a general case, the problem can be solved by the application of tanks in which gas is compressed at a pressure higher than 200 bar, the application of tanks of larger diameters (>250mm), the application of conventional tanks smaller in diameter (250mm) but great in number. As tanks with high pressures above 200 bar are not used and as 4 metres represent the overall maximum bus height allowed, the only possible solution can be found in the storage of a greater number of tanks at a pressure of 200 bar on the roof of a bus and under the floor. Therefore, a smaller trunk compartment has to be widened by tethering an ancillary compartment at the rear end of a bus or optionally by a bus drawn trailer. Obvious difficulties of the CNG application to tourist buses are just one reason for its limited use as propellant in this type of buses.

In any case scenario, if the storage unit is under the floor of a bus, the appropriate ventilation of the space which holds the tanks is provided. This type of storage is avoided with modern bus constructions and it is frequently used with an idea of additionally increasing the tank space so that the vehicle's autonomy could be enhanced.

In a large number of cases in practice, the tanks are placed on the roof of a bus, in specially reinforced holds with gaskets, to which they are fastened with metal strips and they are covered with a decorative and protective lid.

For the other two alternative concepts of gas storage the same rules apply as in the case of compressed natural gas.

3. Effect of a Gas Facility on the Structural Features of a Bus

In order to determine the effect of a gas facility on the structural features of a bus, primarily on the centre of gravity position, the vehicle is regarded as a heterogeneous body comprised of two rigidly connected, concentrated masses with their own distinguishing features. The first mass is the type of bus powered by conventional diesel fuel (henceforth the standard bus) while the second mass is made up of steel tanks which hold gas at a pressure of 200 bar.

Due to the continuous change of mass and passenger disposition in the vehicle during operation, dynamic axle load and centre of gravity position are constantly changing. This fact has to be taken into consideration with every analysis that is performed. Apart from the working load variation due to passengers getting on and off the bus, structural characteristics are also affected by the position of a gas tank.

This paper will investigate the boundary effect (the maximum possible one) of additional mass, so it is considered that the tanks are only situated on the vehicle's roof but not under the floor between the front and rear axle.

With the view of quantifying the effect of gas facilities on the structure of the bus, the IK 104 make (standard bus) is chosen as a starting point, its mass being M_0=9850 kg while a gross vehicle weight rating is M_p=18000kg, height 3090mm, height of landing 900mm, wheelbase 5650mm, total length 11862, front overhang 2820mm, rear overhang 3392mm (Glumac et al., 2002).

Also, the analysis of steering stability is carried out with respect to the application of steel tanks in which natural gas is at a pressure of 200 bar. The proportion of gross vehicle mass to storage capacity amounts to 1.24kg/dm^3, i.e. the mass of a 50-litre gas cylinder with 250mm in diameter without gaseous charge is 62.1kg (Department of Enegy, 2002).

The operational range of at least 350km (with one charge reaching a pressure of 200 bar) calls for 1000 litres of total tank volume. Twenty cylinders are placed in one battery with total length of 7.5m on the roof of a bus. Natural gas mass in 1000 litres of effective area at a pressure of 200 bar amounts to 160kg so that the total mass of one 20 cylinder battery with bearing, joints and 160kg of gas is 1560kg.

Note: Natural gas can be stored in individual containers of diameters larger than 250mm but this has no significant bearing on the centre of gravity height of a CNG powered bus, taking into account the fact that the battery is installed on the vehicle's roof i.e. at a height of around 3000mm.

3.1. Variation in the Centre of Gravity Height

In determining the effect of a gas facility on the bus's centre of gravity height, the analysis is carried out for two cases: for an empty (M_o) and for a full vehicle (M_p).

The initial data for the empty vehicle are: h_t=0.7m; h_t=1.25m; M_o=9850kg; h_g=3.215m; M_g=1560kg; with h_t, M_o, h_g, M_g as the centre of gravity height of a standard bus, mass of a standard bus, centre of gravity height of a battery with CNG cylinders, the battery's mass, respectively. The initial data for the full vehicle differ only in total mass which now amounts to M_p=18000kg.

Bearing in mind the above-mentioned values, it is possible to define the range of a CNG bus's centre of gravity height against the centre of gravity height of a standard diesel bus (Fig. 1).

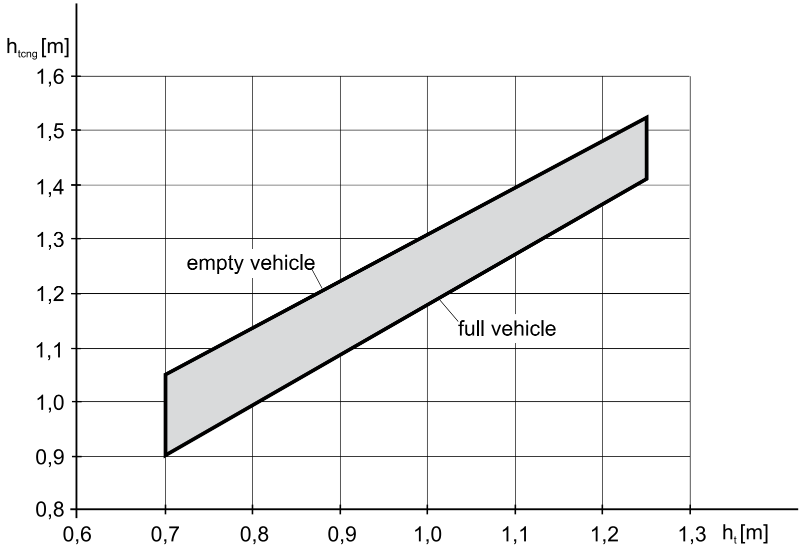

Fig. 1.
Range of a CNG bus's centre of gravity height against the centre of gravity height of a standard diesel bus for partial load $(M_o<M<M_p)$

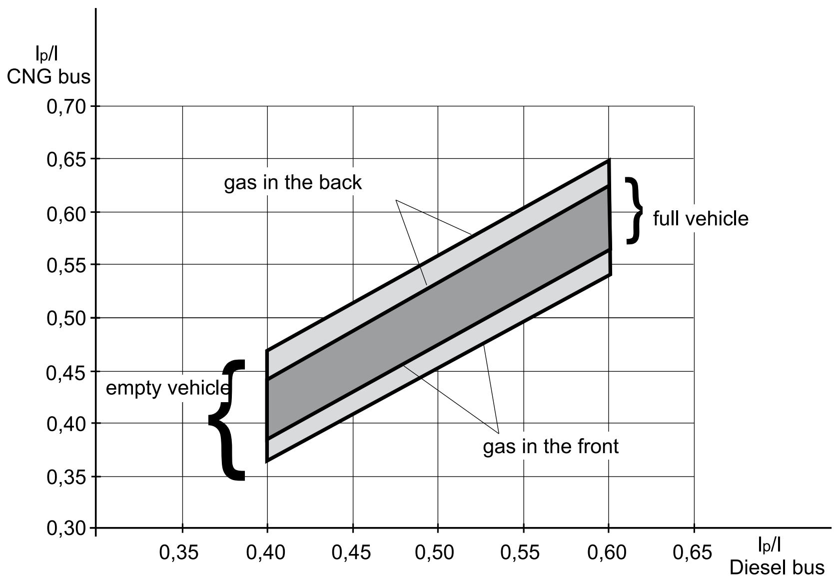

Fig. 2.
Range of l_p/l *centre of gravity value of a CNG bus against* l_p/l *standard diesel bus value for partial load* $(M_o<M<M_p)$

3.2. Change of l_p/l Ratio

In calculating the position of the centre of gravity against the front axle, four different cases can be discerned: gas battery is located in the back of the vehicle, empty bus; gas battery is located in the back of the vehicle, full bus; gas battery is located in the front, empty bus; gas battery is located in the front, full bus. On the basis of data of the preceding values, it is possible to define the range of l_p/l CNG bus value against l_p/l standard diesel bus value (Fig. 2).

4. Steering Stability of a CNG Bus While Braking

The basic parameters of active safety of a vehicle include braking system with its efficiency and reliability characteristics. Braking system greatly affects the possibility of a traffic accident occurrence. With the intent of enhancing the vehicle's safety, braking system should be of high quality in terms of efficiency in order to ensure smaller braking distance, and it should be of high reliability in order to ensure safe and stable vehicle braking at any time.

Another important characteristic in terms of safety is the braking system's adaptability, i.e. its adaptability to different conditions of loads of some axles and to road characteristics (with respect to adherence). As a result, different types of automatic devices for braking force regulation are fitted into the braking system; in most cases, their goal is to prevent wheel locking and thus ensure stability and vehicle control under braking. But even with these devices within the braking system's transmission mechanism, there is no feedback (or it is not "quick" enough) on the effects of achieved control of braking forces within regulatory circuit which might lead to the available adhesion being exceeded (Janković and Todorović, 1996). This is when the wheels are locked up i.e. they are prone to slipping on the road in translatory manner. In this kind of situations, the wheel is almost incapable of ensuring reaction to any kind of external obstruction so that the vehicle which is moving with multiple locked wheels is considered unstable.

Unbalanced or perturbation forces are of stochastic nature and might appear under braking. Not considering their intensity, the implications they might involve, in terms of changing the desired or initial trajectory of the vehicle's centre of mass, are mostly evident under braking when the wheel of some axel or all axels is locked laterally, due to the smallest reserve of available adhesion.

The concept of the "steering stability of a vehicle", defined in the introduction of the paper and with regard to CNG buses, can be analysed on the basis of Lyapunov's method. According to Lyapunov's method, the motion of a material system will be stable if small perturbations affect the initial motion and even if this disturbed motion is slightly different from the initial motion, regardless of how much time has passed since the moment the perturbation happened. If the vehicle, which is moving on the rectilinear and curvilinear part of the road at a constant speed, becomes affected by a small perturbation, represented through the velocity of the centre of mass in lateral direction V_{Tn} and the initial angular velocity Ψ, and even if the vehicle continues to move rectilinearly and curvilinearly and the obtained perturbation is throttled, the motion of the vehicle will be stable. If the perturbation is not throttled, the motion is unstable. In this part of the paper, we will investigate the steering stability of a bus, the motion of a CNG bus during braking on the rectilinear section of a road with lateral elastic wheels for three characteristic cases: rear-axle wheels locked up while braking, front-axle wheels locked up while braking and both axles' wheels locked up while braking.

5. Differential Equations of Motion

Differential equations of motion for the case of locked front wheels of a bus are formed according to the mode of a bus shown in Fig. 3. The bus is viewed as a rigid body which makes planar motion. Lateral reactions in the footprint of a tyre and road are replaced by one force each, which act at the centre of the front and rear axle. Also, tangential forces are considered to act upon the vehicle's centre of mass "T" in the direction of the longitudinal axis. The motion of a bus is monitored against the fixed coordinate system Oξη. Since we are dealing with planar motion, the position of a vehicle is determined by two coordinates ξ and η which define the current pole and angle of rotation (Ψ) of the body around the axis which is perpendicular to the plane of the carriageway, and it goes through the movable (current) pole.

Equations of motion formulated on the basis of Fig. 3 are given in the form of Eq. (3) and Eq. (4):

$$\frac{dV_{Tn}}{dt}-\left(\frac{l_z\cdot K_{\delta z}-l_p\cdot\varphi\cdot Z_p}{m\cdot V}-v\right)\cdot\omega+\left(\frac{\varphi\cdot Z_p+K_{\delta z}}{m\cdot V}\right)\cdot V_{Tn}=0 \quad (3)$$

$$\frac{d\omega}{dt}+\left(\frac{l_z^2\cdot K_{\delta z}+l_p^2\cdot\varphi\cdot Z_p}{I_i\cdot V}\right)\cdot\omega-\left(\frac{l_z\cdot K_{\delta z}-l_p\cdot\varphi\cdot Z_p}{I_i\cdot V}\right)\cdot V_{Tn}=0 \quad (4)$$

coefficients are:

$$\frac{l_z^2\cdot K_{\delta z}+l_p^2\cdot\varphi\cdot Z_p}{I_i\cdot V}=A, \quad \frac{l_z\cdot K_{\delta z}-l_p\cdot\varphi\cdot Z_p}{I_i\cdot V}=B,$$

$$\left(\frac{l_z\cdot K_{\delta z}-l_p\cdot\varphi\cdot Z_p}{m\cdot V}-v\right)=C, \quad \left(\frac{\varphi\cdot Z_p+K_{\delta z}}{m\cdot V}\right)=D$$

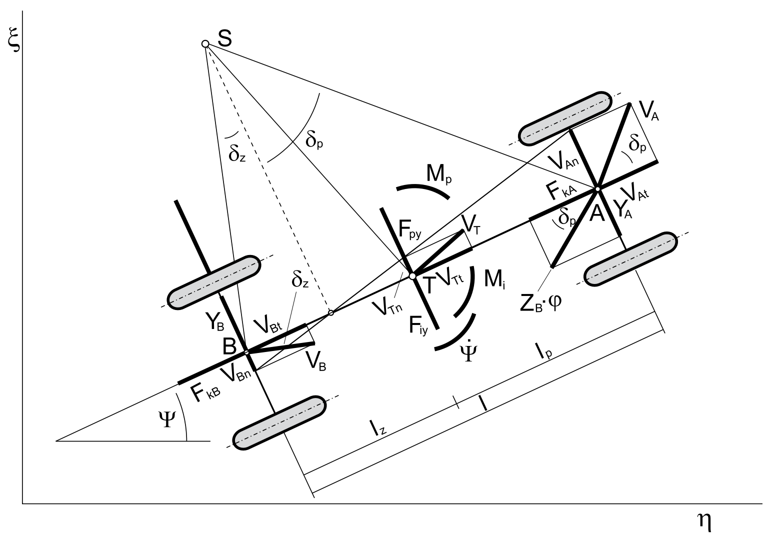

Fig. 3.
Kinematic dynamic scheme of a CNG bus model, front wheels locked

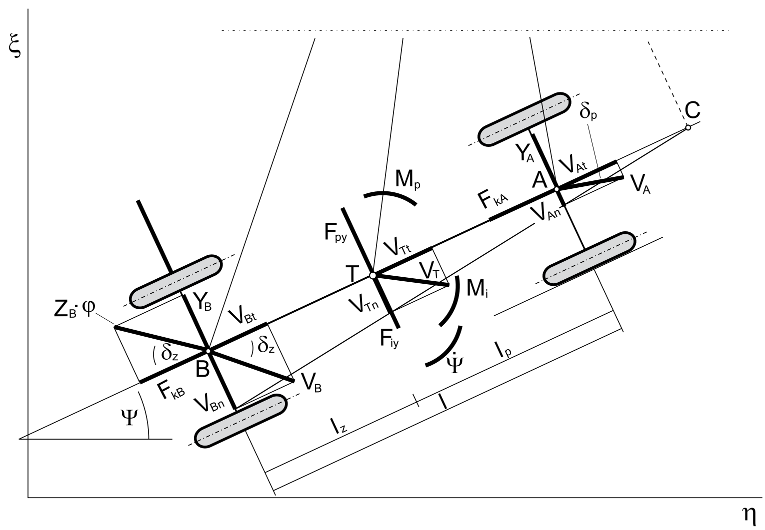

Fig. 4.
Kinematic dynamic scheme of a CNG bus model, rear wheels locked

On the basis of the Routh-Hurwitz criterion, the stability condition is met if the following applies, Eq. (5) and Eq. (6):

$$A \cdot D - B \cdot C > 0 \tag{5}$$

$$l_z^2 \cdot K_{\delta z} \cdot \varphi \cdot Z_p + l_p^2 \cdot K_{\delta z} \cdot \varphi \cdot Z_p + 2 \cdot l_p \cdot l_z \cdot K_{\delta z} \cdot \varphi \cdot Z_z - m \cdot V^2 \cdot \left(K_{\delta z} \cdot l_z - \varphi \cdot Z_p \cdot l_p\right) > 0 \tag{6}$$

By means of the preceding two expressions, the relation for critical velocity is obtained, Eq. (7):

$$V_{kr} = \sqrt{\frac{K_{\delta z} \cdot \varphi \cdot Z_p \cdot l^2 \cdot g}{G \cdot \left(l_z \cdot K_{\delta z} - l_p \cdot \varphi \cdot Z_p\right)}} \tag{7}$$

where: $K_{\delta z}$ is the coefficient of resistance to tyre deflection, φ is the adhesion coefficient.

If $V<V_{kr}$, the motion of a bus is stable, if $V>V_{kr}$, the motion of a bus is unstable and if $V=V_{kr}$, the motion of a bus is in the state of unstable equilibrium.

In the case of locked rear wheels, the coefficient A, B, C and D gained on the basis of the characteristic differential equation and kinematic dynamic scheme (Fig. 4) of the bus for this case are stated by means of the following relations:

$$\frac{l_p^2 \cdot K_{\delta p} + l_z^2 \cdot \varphi \cdot Z_z}{I_i \cdot V} = A, \quad \left(\frac{l_p \cdot K_{\delta p} - l_z \cdot \varphi \cdot Z_z}{I_i \cdot V}\right) = B,$$

$$\left(v + \frac{l_p \cdot K_{\delta p} - l_z \cdot \varphi \cdot Z_z}{m \cdot V}\right) = C, \quad \left(\frac{K_{\delta p} + \varphi \cdot Z_z}{m \cdot V}\right) = D$$

so it is, Eq. (8)

$$V_{kr} = \sqrt{\frac{K_{\delta p} \cdot \varphi \cdot Z_z \cdot l^2 \cdot g}{G \cdot \left(l_p \cdot K_{\delta p} - l_z \cdot \varphi \cdot Z_z\right)}} \tag{8}$$

In the case of all wheels being locked (Fig. 5), it will be:

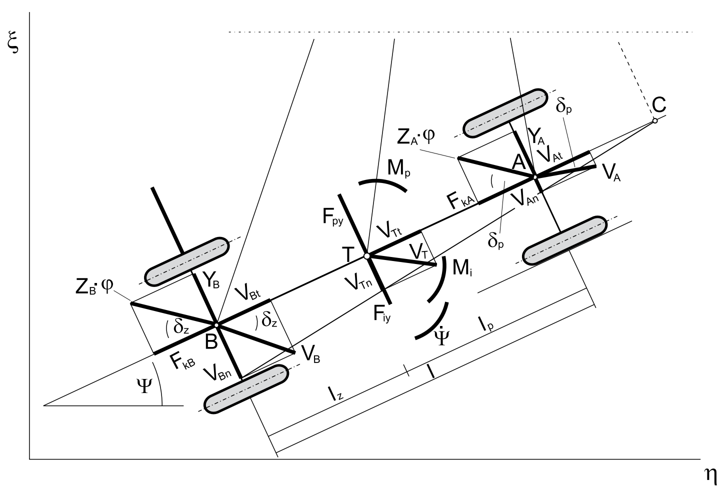

Fig.5.
Kinematic dynamic scheme of a CNG bus model, all wheels locked

$$\frac{l_p^2 \cdot \cdot \varphi \cdot Z_p + l_z^2 \cdot \varphi \cdot Z_z}{I_i \cdot V} = A \;, \quad \left(\frac{l_p \cdot \varphi \cdot Z_p - l_z \cdot \varphi \cdot Z_z}{I_i \cdot V} \right) = B \;,$$

$$\left(v + \frac{l_p \cdot \varphi \cdot Z_p - l_z \cdot \varphi \cdot Z_z}{m \cdot V} \right) = C \;, \quad \left(\frac{\varphi \cdot Z_p + \varphi \cdot Z_z}{m \cdot V} \right) = D$$

so it is, Eq. (9)

$$V_{kr} = \sqrt{\frac{\varphi^2 \cdot Z_p \cdot Z_z \cdot l^2 \cdot g}{G \cdot \left(l_p \cdot \varphi \cdot Z_p - l_z \cdot \varphi \cdot Z_z \right)}} \tag{9}$$

6. Result and Analysis

The diagrams of the dependence of critical velocity on structural features of a bus and operation conditions for all three cases of wheels lock, by means of which the analysis of the steering stability of a CNG bus is carried out, are represented in Figs. from 6 to 17.

In the shown diagrams, the dependence of critical velocity on structural parameters of the bus for three characteristic cases is given: front-axle wheels locked, rear-axle wheels locked and both axles' wheels locked. Since we are dealing with the non-stationary regime of the vehicle's motion, the critical velocity depends on a great number of parameters. Apart from the position of the centre of gravity with respect to the rear axle l_p (l_p/l) and total mass of the bus, the value V_{kr} is affected by the adhesion coefficient and centre of gravity height. The effect of the centre of gravity height and available adhesion is evidenced by the change of axle pressures while braking against the stationary regime of motion, Eq. (9) and Eq. (10):

$$Z_{pk} = G \cdot \cos\alpha \cdot \frac{l_z + h_t \cdot (\varphi + f)}{l} \tag{9}$$

and

$$Z_{zk} = G \cdot \cos\alpha \cdot \frac{l_p - h_t \cdot (\varphi + f)}{l} \tag{10}$$

In the first case (Fig. 6) when the bus is empty, front wheels are locked and CNG tanks are located in the back of the vehicle, critical velocity is defined for the entire range of values l_p/l from 0.400 to 0.800 (with regard to l_p/l of a standard bus). Since available adhesion on the rear axle is completely used (but no slip occurred), critical velocity increases with the shift of the centre of gravity towards the back part of the bus because the rear-axle load increases. The stability of motion largely depends on the adhesion coefficient value. For very small values φ, critical velocity is within boundaries of 5m/s±10% (this is the case with locked rear wheels at minimum and maximum bus load for both bus conceptions, only in the case of all wheels being locked does the V_{kr} have values even up to 8m/s at φ=0,3). For large values of adhesion coefficient (φ=0,8) with front-axle wheels locked up and tank storage in the back, the increase of critical velocity with regard to the conception with no CNG tank for l_p/l equals 7,638m/s. With the centre of gravity height decrease, the difference in speed drops and the effect of gas facility on the stability of motion is weaker.

On the basis of Fig. 7, it is noted that, with rear axle off-load, storing of the tank in the front of the bus, critical velocity decreases for ΔV=8,537m/s at l_p/l=0,8, h_t=1,519 and φ=0,8 and ΔV=4,020m/s at l_p/l=0,8, h_t=1,044m and φ=0,8. With the decrease of l_p/l, φ and h_t values, the variation in speed is negligible and the effect of gas facility is less obvious.

Complete utilisation of bus capacities (Fig. 8 and Fig. 9) leads to significant changes in the values of critical velocity. In four cases at φ=0,8 ht=1,407m, h_t=1,250m, h_t=0,901m (Fig. 8, gas in the back) and φ=0,8 ht=1,407m (Fig. 9, gas in the front) V_{kr} is not defined for the corresponding values of l_p/l, which indicates that the effect of total mass for large values of adhesion coefficients is significant. CNG tanks make the asymptote find itself between the values of l_p/l 0,720 i 0,740. If maximum bus speed is taken into consideration, l_p/l which defines the stable area of motion is decreased and its value is 0,67 which is more favourable from the aspect of stability with regard to no gas conception.

In case of locked rear-axle wheels (Fig. 10, Fig. 11, Fig. 12 and Fig. 13), the fluctuation of critical velocity with regard to the structural features of a bus are far less violent compared to the case of locked front-axle wheels. The absence of a greater change for the entire range of l_p/l values is particularly noticeable when the vehicle is empty (V_{min}=5,605m/s, for h_t=1,519m and φ=0,8; V_{max}=7,095, for h_t=0,7m and φ=0,8). With complete utilisation of bus capacities, the decrease of critical velocity is obvious with raised values of l_p/l for small centre of gravity height (h_t=0,7m, when CNG tanks are placed in the back) while at larger values h_t, the function V_{kr}=f (l_p/l, φ, h_t) has a maximum of 6,971m/s at l_p/l=0,540, φ=1,407 and h_t=0,8m. When compressed gas is stored in the front of the bus, the curves of the dependence of critical velocity on the vehicle's structural features are of the same nature as in the previous case, with little deviations.

When both axles' wheels are locked during braking (Fig. 14, Fig. 15, Fig. 16, and Fig. 17) the effect of the gas facility on the stability of motion is unfavourable since critical speeds are lower (with regard to V_{kr} values of a standard bus) for all variants, whether the vehicle is empty or full or whether CNG tanks are stored in the front or back of a bus. Since maximum value of change V_{kr} is less than 1,5m/s, by examining the diagrams and noticing the closeness of curves, it is concluded that the effect of a CNG tank while braking with locked wheels of both axles is quantitatively negligible.

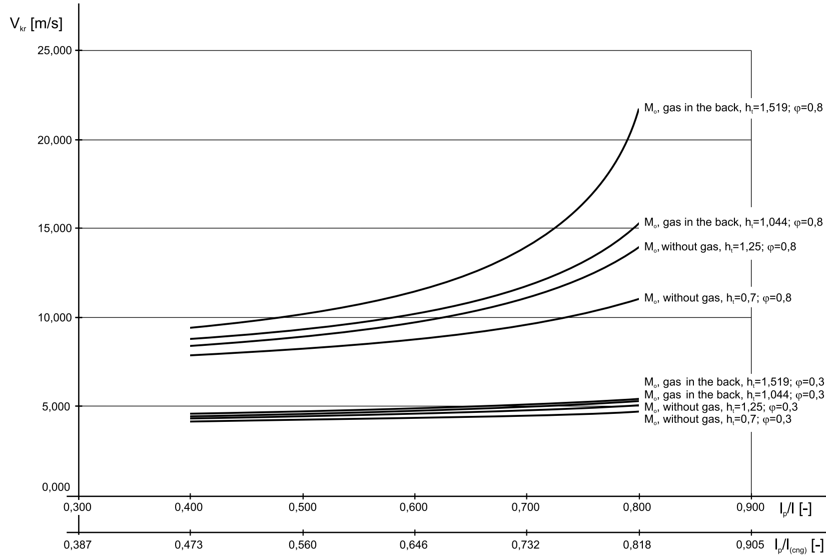

Fig. 6.
Dependence of critical velocity of stable steering on structural features of a standard and CNG bus, (empty vehicle M=M_o, gas in the back, front wheels locked).

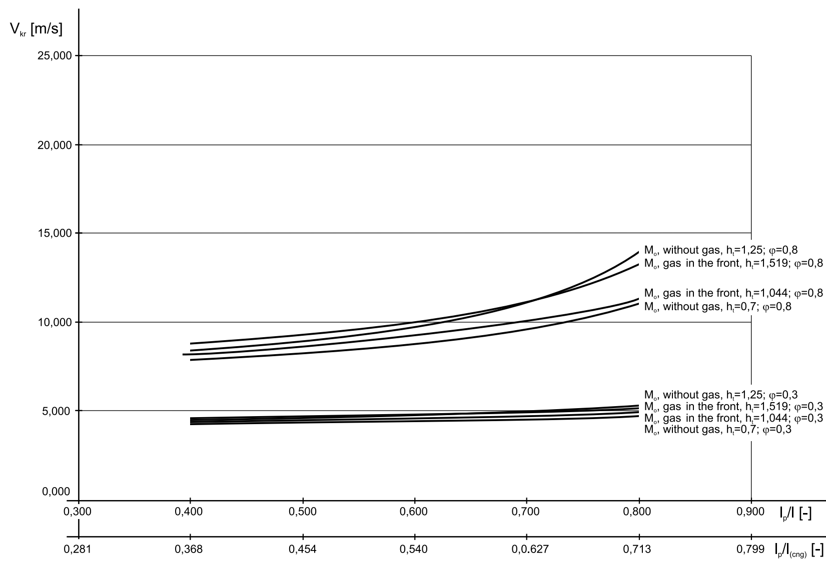

Fig. 7.
Dependence of critical velocity of stable steering on structural features of a standard and CNG bus (empty vehicle M=M_o, gas in the front, front wheels locked)

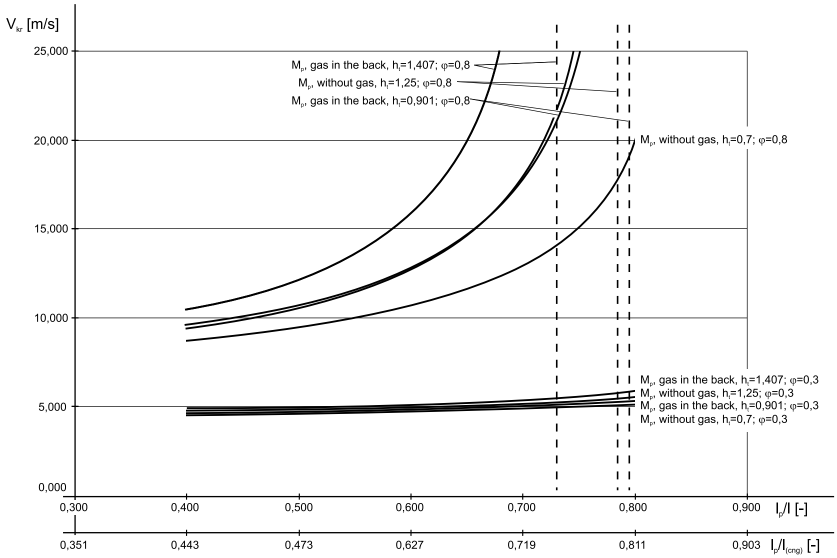

Fig. 8.
Dependence of critical velocity of stable steering on structural features of a standard and CNG bus, (full vehicle M=M_p, gas in the back, front wheels locked)

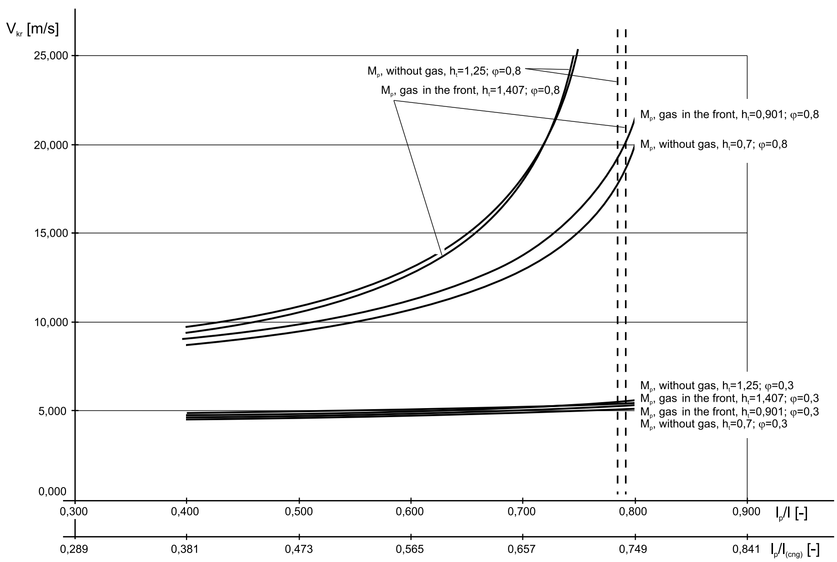

Fig. 9.
Dependence of critical velocity of stable steering on structural features of a standard and CNG bus, (full vehicle M=M_p, gas in the front, front wheels locked)

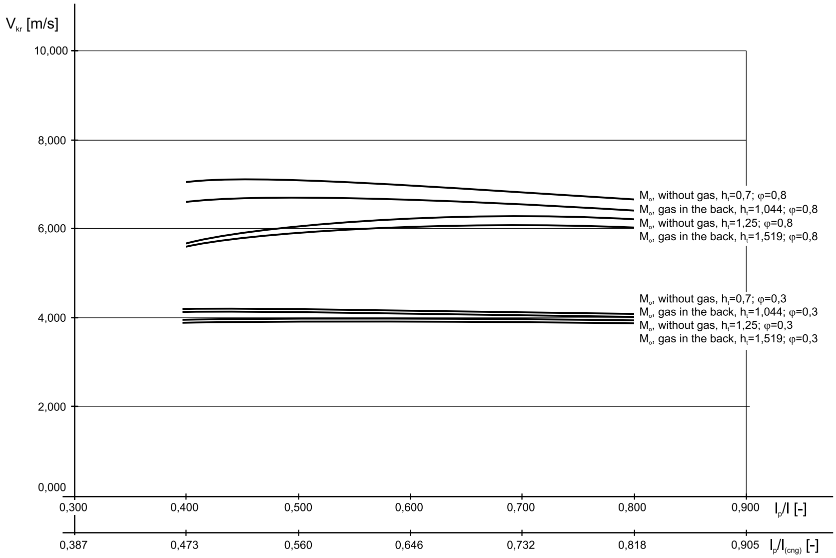

Fig. 10.

Dependence of critical velocity of stable steering on structural features of a standard and CNG bus, (empty vehicle M=M_o, gas in the back, rear wheels locked)

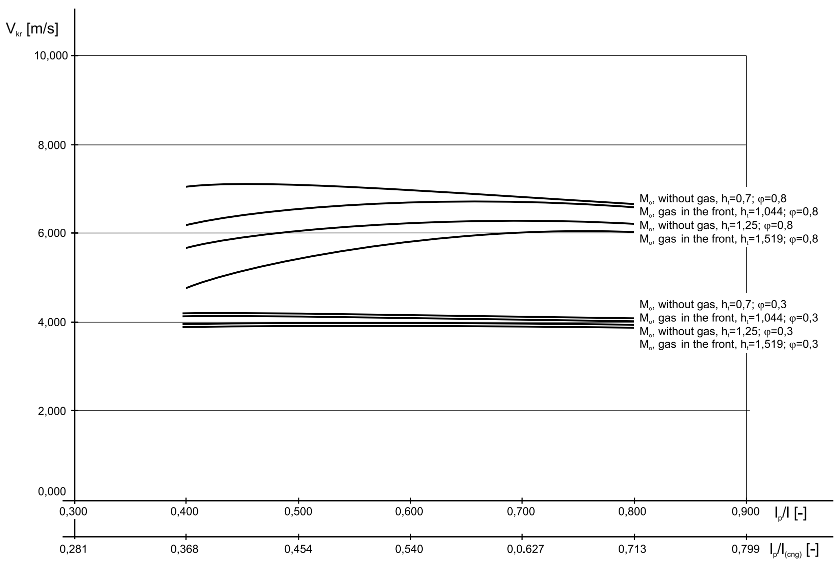

Fig. 11.

Dependence of critical velocity of stable steering on structural features of a standard and CNG bus, (empty vehicle M=M_o, gas in the front, rear wheels locked)

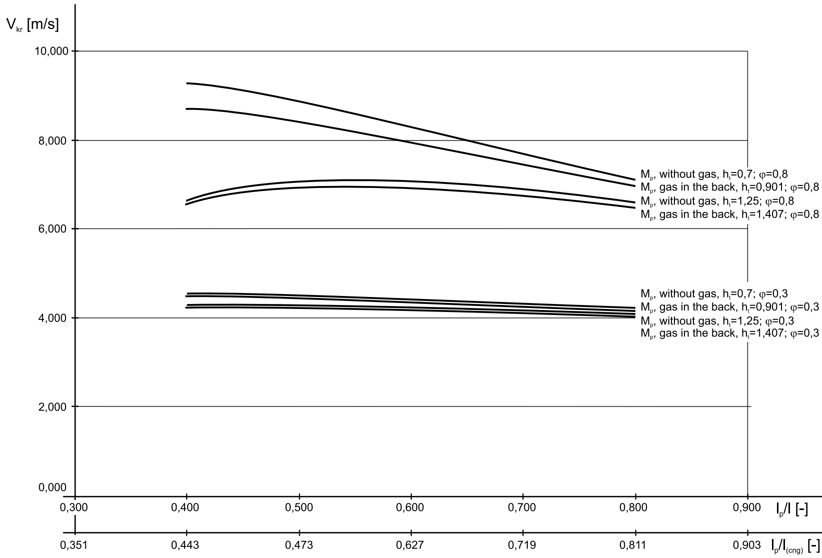

Fig. 12.

Dependence of critical velocity of stable steering on structural features of a standard and CNG bus, (full vehicle $M=M_p$, gas in the back, rear wheels locked)

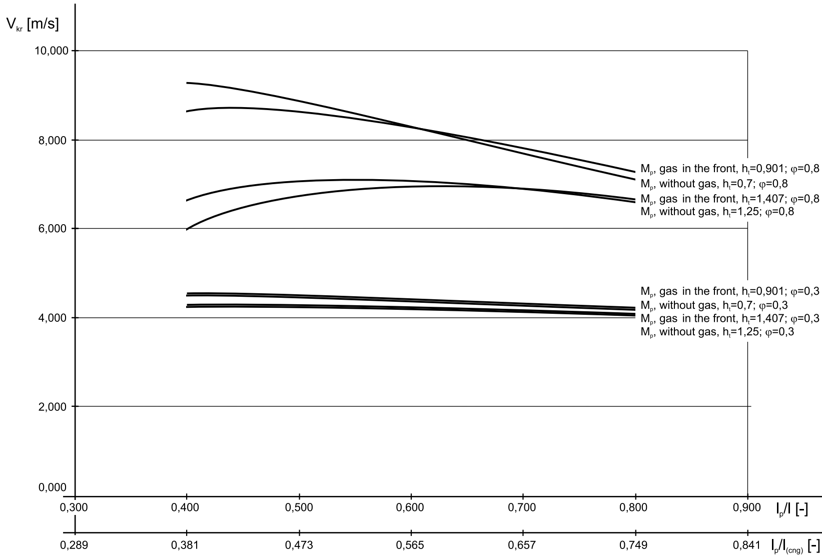

Fig. 13.

Dependence of critical velocity of stable steering on structural features of a standard and CNG bus, (full vehicle $M=M_p$, gas in the front, rear wheels locked)

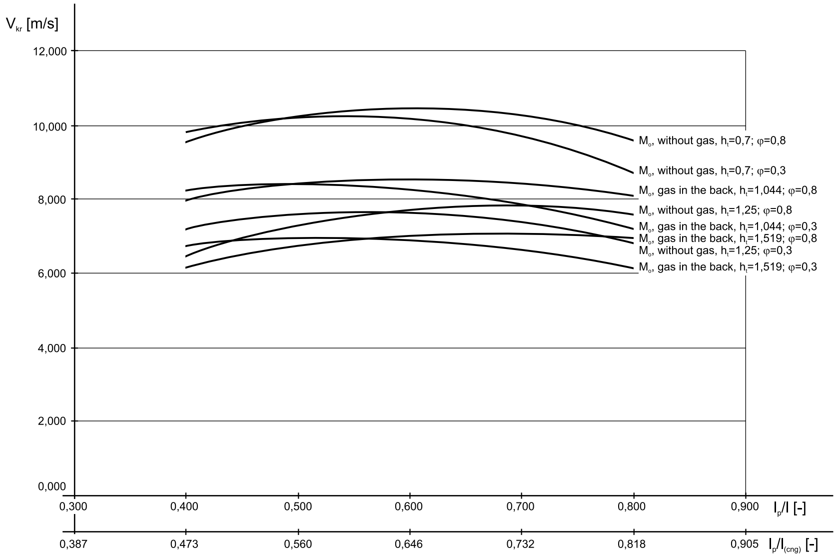

Fig. 14.
Dependence of critical velocity of stable steering on structural features of a standard and CNG bus (empty vehicle $M=M_o$, gas in the back, all wheels locked)

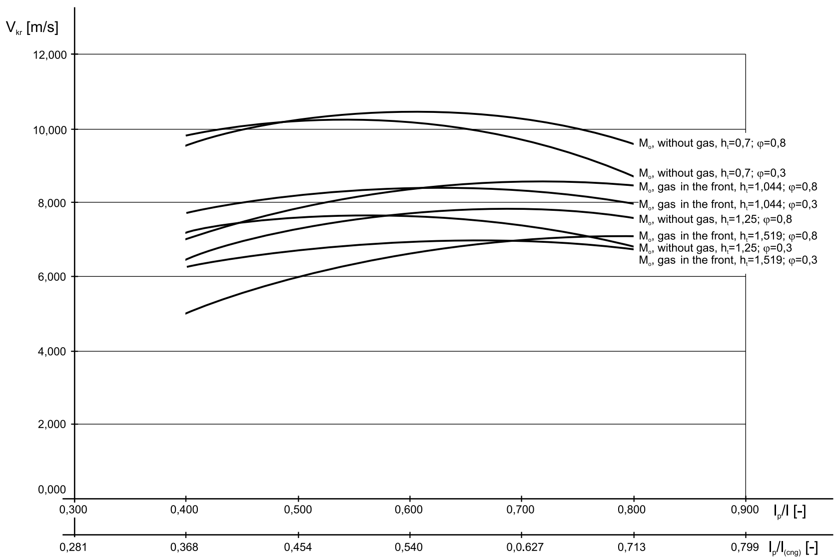

Fig. 15.
Dependence of critical velocity of stable steering on structural features of a standard and CNG bus (empty vehicle $M=M_o$, gas in the front, all wheels locked)

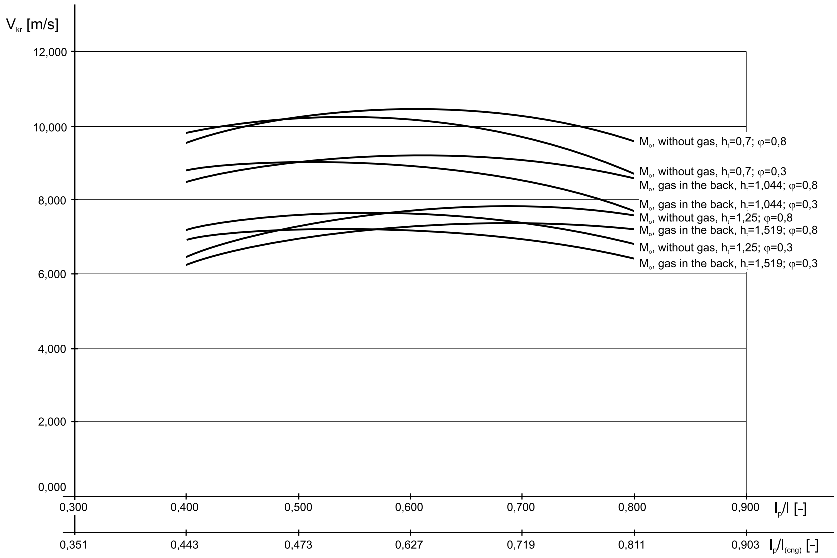

Fig. 16.

Dependence of critical velocity of stable steering on structural features of a conventional and CNG bus (full vehicle $M=M_p$, gas in the back, all wheels locked)

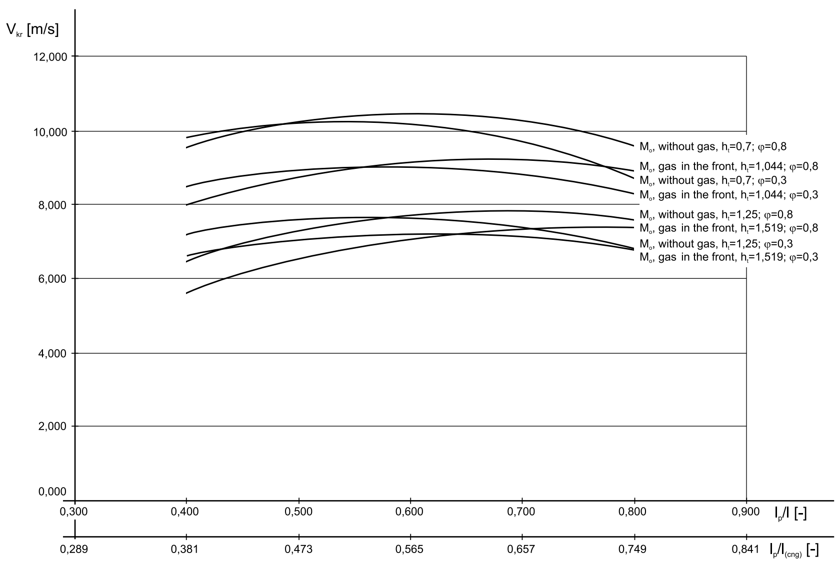

Fig. 17.

Dependence of critical velocity of stable steering on structural features of a standard and CNG bus (full vehicle $M=M_p$, gas in the front, all wheels locked)

6. Conclusion

With the view of maximising possible positive or negative effects of the application of natural gas for bus propulsion on the stability of motion in different situations, the analysis is carried out with regard to gas storage in conventional steel tanks of distinctive mass $M/V=1,2kg/m^3$.

For this kind of initial condition, the following conclusions can be made:

- When braking with locked front wheels and gas in the back of the vehicle, the steering stability is enhanced. Increase in the total mass of the bus entails enhancement of the stability area limited by the function $V_{kr}=f\ (l_p/l,\ h_t,\ \varphi,\ M_u)$. If CNG tanks are located in the front of the vehicle, according to the values of the change in critical velocity ($\Delta V<0,8m/s$), it is concluded that the effect of the gas facility is negligible, in both positive and negative sense.

- When rear-axle wheels are locked, the location of the tank on the roof of a bus (in the front or back) does not affect the steering stability but certain positive changes are reflected in the case of maximum bus load, with the relation of $l_p/l<0,6$ and the centre of gravity height smaller than 1m.

- Negative consequences caused by the application of compressed natural gas at locked wheels of both axles are reflected in the maximum decrease of critical velocity of 1.5 m/s for all values of the l_p/l relation, small centre of gravity height and large values of the adhesion coefficient when the bus is unloaded. In all other variants, a CNG tank has little effect on the steering stability.

Acknowledgements

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STABILNOST UPRAVLJANJA AUTOBUSA SA POGONOM NA PRIRODNI GAS U TOKU KOČENJA

Ivan Ivković, Željko Janjoš, Srećko Žeželj

Sažetak: Upotreba prirodnog gasa kao pogonskog goriva autobusa uslovljava pored primene pogonskog agregata prilagođenog korišćenju prirodnog gasa i primenu odgovarajuće gasne instalacije. U prvom delu rada prikazane su specifičnosti vezane za smeštaj rezervoara sa komprimovanim prirodnim gasom kao glavnim nosiocima dodatne mase usled korišćenja ovog energenta za pogon autobusa, kao i njihov uticaj na konstrukcione karakteristike vozila. Drugi deo rada obuhvata formiranje i analizu diferencijalnih jednačina po pitanju stabilnosti upravljanja, koje opisuju kretanje autobusa na gas sa svojim konstrukcionim karakteristikama, prema definisanim modelima za slučajeve kočenja autobusa sa blokiranim prednjim, zadnjim i svim točkovima.

Ključne reči: prirodni gas, CNG autobus, stabilnost upravljanja.