Analysis of Possible Ways of Power Distribution in an All-wheel Drive Vehicle

A. Keller, S. Aliukov

***Abstract*—The main indicators for mobility of a multipurpose wheeled vehicle are the maximum and average technical velocity, and they are mainly determined by power-to-weight ratio and the parameters of the suspension. As our analysis shows, with the increase of the power-to-weight ratio of the vehicle and its weight, the growth rate of the velocity is reduced, and after reaching a certain value, the velocity remains almost constant. This is due to the fact that for operating conditions of the multi-purpose wheeled vehicle, movement on roads with different degrees of uneven distribution of the rolling resistance and adhesion, in both transverse and longitudinal directions, is typical.**

In this investigation we evaluate the effectiveness of the main methods of power distribution between the drive wheels of the multi-purpose wheeled vehicles: disabling of drive axles, blocking of cross-axle and inter-axle differentials, and a slowdown of slipping wheel movement.

It was revealed that the transmission of a promising multipurpose wheeled vehicle has to be modernized in the following ways: 1) all-wheel drive with the rational value of the gear ratio of inter-axle differential; 2) realization of the possibility of periodic shutdown of the drive axles when road conditions are good, or turning on the additional driving axles of the trailer when the road conditions require significant drive forces and torques; 3) providing of limited excess capacity of power unit by reducing the fuel supply or applying braking torque to the slipping wheels; 4) providing of rigid kinematic connection in the movement process with compensation of the kinematic mismatch by adjusting of air pressure in the tires.

At present, the effectiveness of the proposed methods of power distribution has been investigated in different extent. Thus, there arises the problem of the complex evaluation of the effectiveness of methods of the power distribution between the drive wheels of the multi-purpose wheeled vehicle. This investigation is directed towards evaluating the effectiveness of power distribution in mechanical transmission.

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***Index Terms*—comparative analysis, power distribution, transmission**

I. INTRODUCTION

IT is well known that the main indicators for mobility of a multipurpose wheeled vehicle are the maximum and average velocities, and they are mainly determined by the specific power of engine [1-4]. Besides, the average velocity on dirt roads with satisfactory condition is defined by the parameters of suspension as well. However, analysis shows that when the specific power increases, growth rate of the velocity decreases, reaching a certain value when the velocity does not increase substantially [5,6]. This is due to the fact that for operating conditions of the multi-purpose wheeled vehicle on probable strategic directions, movement on roads with different degrees of uneven distribution of the rolling resistance and adhesion, in both transverse and longitudinal directions, is typical [7-9]. Therefore, to enhance mobility of such a multipurpose wheeled vehicle, it is necessary to improve the design of its chassis, including power distribution schemes.

II. METHODS OF POWER DISTRIBUTION IN MECHANICAL TRANSMISSION

The most rational concept for modernization of the multipurpose wheeled vehicle is concept of functioning of transmission, presented in Fig. 1 [1].

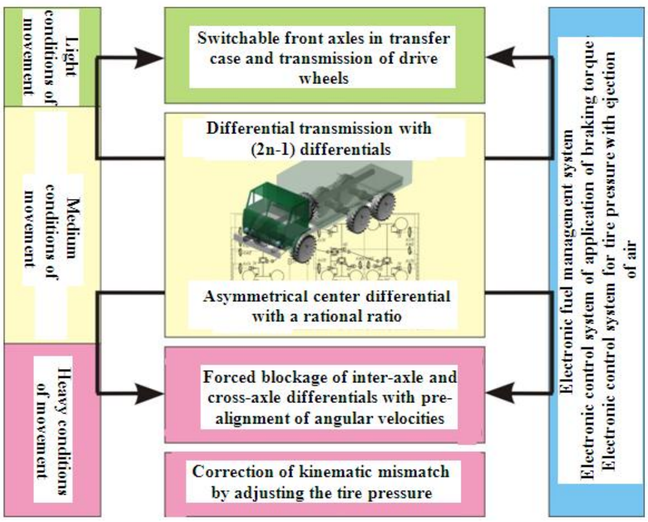

Fig. 1. Concept for operation of transmission of a multi-purpose wheel vehicle

On mode of acceleration up to 30 km/h, a rigid kinematic connection between the driving axles and wheels of unmanaged axels should be switched on. After reaching velocity of 30 km/h it is provided disconnection of the rigid link and then differential connection between the drive wheels. Upon reaching of steady velocity and slippage of the drive wheels less than 5%, front axle is switched off. With increasing of the slippage of the drive wheels more than 5%, full differential drive is switched on.

In the case of movement in difficult road conditions with substantial forces of external resistances and inhomogeneous footprint, rigid kinematic connection is involved. In this case, we have to provide alignment of angular velocity of the connected axels by reducing the fuel supply or application of braking torque to the slipping wheels.

Compensation of the kinematic inconsistency, arising in the process of movement, is carried by regulation of air pressure in the tires.

The effectiveness of the proposed methods of power distribution is currently being studied in different extents. Therefore, there arises the problem of the complex evaluation of the effectiveness of the methods of distribution of power among the drive wheels of a multi-purpose wheeled vehicle.

In this paper we offer to divide methods of power distribution into 4 groups:

- method of partial solutions, in which constant value of coefficient of the power distribution is selected (for instance, the gear ratio of the center differential), which satisfies the greatest number of possible traffic conditions;
- method of periodic action, in which the transition from a continuous distribution of power among all drive axles and wheels of the vehicle to periodic distribution. For example, switching off part of the driving axles when driving on good road conditions or switching on more driving axles of the trailer when driving in conditions requiring large thrust forces;
- method of limiting of excessive action in which excess capacity of the engine is reduced by reducing the fuel supply or the application of braking torque to the slipping wheels;
- method of implementation of a rigid kinematic coupling in which the possibility of relative rotation of the drive wheels is eliminated. It allows us to distribute torque proportionally to the towing capabilities of the drive wheels.

A. *Method of partial solutions*

It is found that in multi-purpose wheeled vehicle with a center differential, having an uneven distribution of weight on the drive axles, there are additional losses of power due to the uneven distribution of thrust forces among the drive wheels. When driving on a solid support surfaces, these power losses can be up to 3-8% of the total power required for the movement of multi-purpose wheeled vehicle. There is a clear area of low power losses, corresponding to a particular gear ratio of the center differential.

It is possible to solve the problem of reducing the power losses and improving traction and speed properties by applying of differential mechanism with rational gear ratio in the axle drive.

In this paper we have derived expressions for the determination of gear ratio of the center differential of the multi-purpose wheeled vehicle when driving on non-deformable bearing surface [5]:

$$k = \frac{f\left(\alpha+\beta\left(R_2/4\right)^2\right)R+P\left(\alpha+\beta\left(R_1/2\right)^2\right)}{(fR+P)\left(\alpha+\beta\left(R_1/2\right)^2\right)}\frac{R_2}{R_1}, \quad (1)$$

here α and β are empirical coefficients, f, P, R, R_1, R_2 are parameters that are constant for a given tire.

The results of calculation, that are given Table I, indicate that for each road and load conditions a certain ratio of the center differential is required.

TABLE I
RATIONAL RATIO OF CENTER DIFFERENTIAL OF VEHICLE OF TYPES: 4X4, 6X6, 8X8

Road conditions		Deferential ratio for different MWV		
		4X4 (KAMAZ-4350)	6X6 (KAMAZ-5350)	8X8 (KAMAZ-6350)
Expected rational ratio	Paved roads	1.2	2.62	1.12
	Roads with gravel or cobble pavement	1.31	2.84	1.18
	Unpaved roads: satisfactory condition	1.32	2.86	1.21
	broken	1.34	2.88	1.23
Ratio of center differential		1.30	2.82	1.19

Evaluation of the effectiveness of the proposed gear ratios of the center differential was conducted by simulation of movement on a standard route of multipurpose wheeled vehicle (MWV), for the following types: 6X6 (KAMAZ-5350) with serial transmission (with asymmetrical locked center differential with a gear ratio which is equal to 2) multi-purpose wheeled vehicle with the recommended gear ratio of the center differential which is equal to 2.8 (MWV type I), and MWV with optimized power distribution. These types are the most popular and therefore the most interesting for us. The simulation results are presented in Fig. 2 [1].

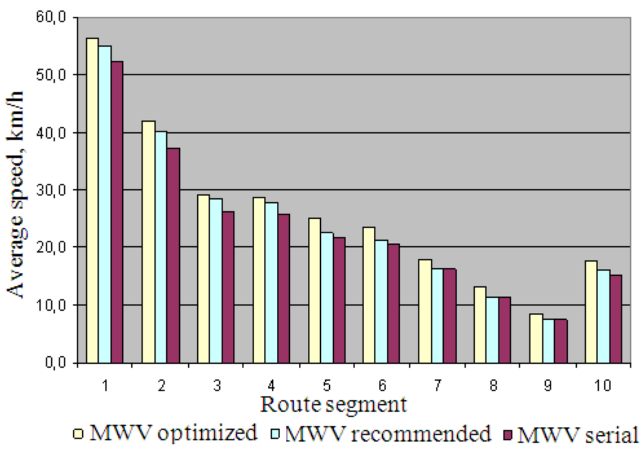

Fig. 2. Comparative assessment of mobility of MWV 6X6 with various methods of power distribution

Analysis of the results shows that the multi-purpose wheeled vehicle equipped with center differential with the recommended gear ratio improves the average speed on solid support surfaces up to 5-9%. Besides, it reduces fuel consumption up to 6-8% in comparison with standard multi-purpose wheeled vehicles.

B. Method of introducing a rigid kinematic connection

It is found that the method of introducing a rigid kinematic connection has two major drawbacks: difficulty with the introducing the connection in the process of movement of the multi-purpose wheeled vehicle and redistribution of torque due to the inevitable kinematic inconsistency.

To realize this method of introducing a rigid kinematic connection, we developed a new design of the center differential combined with a freewheel (Fig. 3) [5].

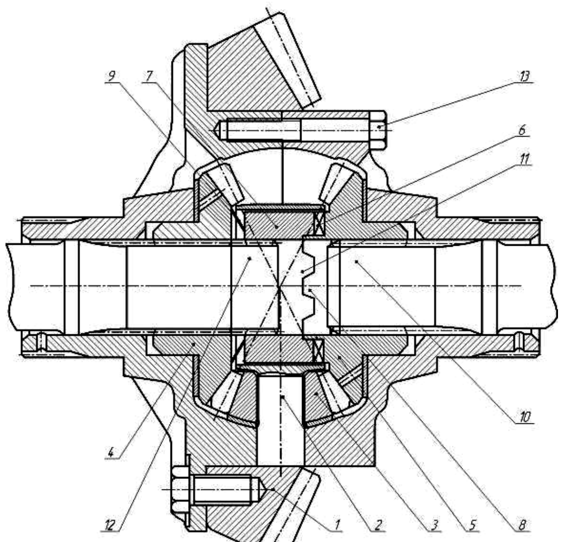

Fig. 3. Differential with freewheel (Patent of the Russian Federation for useful model №22810): 1 - body; 2 - crossing; 3 - satellites; 4, 5 - side gears; 6 - cams rectangular profile; 7 - slotted sleeve; 8 - the central ring; 9 - diaphragm spring; 10, 12 - the half shafts; 11 - teeth of trapezoidal profile

In this paper, the expediency of applying braking torque to the slipping wheels and reducing of fuel delivery for preliminary alignment of the angular velocities of the slipping wheels and subsequent lock-axle and cross-axle differentials.

Significant impact on the effectiveness of the method of introducing the rigid kinematic connection has kinematic mismatch between the bridges of the multipurpose wheeled vehicle.

Graphs of thrust and the specific thrust depending on the number of bridges of the multi-purpose wheeled vehicle when driving on a clay road are presented in Fig. 4.

Analysis of the Fig. 4 suggests that in certain kinematic mismatch (about 8.5%) among the driving axles implemented thrust with the number of driving axles more than three may be reduced. The specific thrust in the presence of kinematic inconsistency always decreases with increasing of the number of driving axles.

Using the suggested method can increase the average speed of the vehicle on sodden dirt roads and off-road up to 6-8% and reduce fuel consumption up to 10-15% in comparison with serial multi-purpose wheeled vehicle. In general, the complex application of the proposed methods of partial solutions (rational gear ratio of center differential) and the introduction of a rigid kinematic connection allows us to increase the average speed up to 6-10% and reduce fuel consumption up to 5-10%.

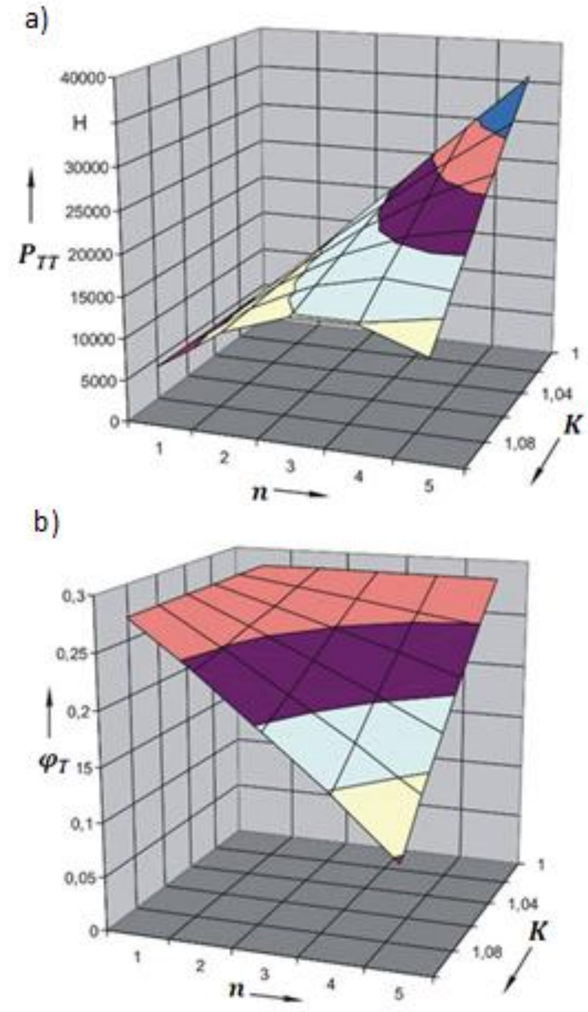

Fig. 4. The graphs of: a) the total thrust P_{TT} ; and b) the specific thrust φ_T depending on the number of driving axles n and kinematic inconsistency K

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C. Method of periodic action

In this paper, the expediency of the shutdown of some drive axles is proved. Boundary condition for inclusion in the work of the axle is the excess loss slippage in running wheels in comparison with the power loss in the drive axle.

From equations of power balance for different schemes of transmission [1], the expressions for the determination of parameters transmission are obtained. One of the measures of efficient of transmission is power loss [1]. The coefficient of efficiency of the transmission is the ratio of power loss in no all-wheel drive scheme to the loss of power in all-wheel

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drive scheme. On the basis of the expressions there were defined optimal modes of switching on the front drive axle for vehicle of type 4x4 (KAMAZ-4350), 6X6 (KAMAZ-5350) (Table II). The data in the Table II show the rational conditions to switch the front axle on. It is the most useful when driving with slippage more than 5%. Number of drive wheels is determined by selecting the highest (rounded up to an even integer) number from received ones under the following conditions:

TABLE II
WEIGHT OF TOWED TRAILER, IN WHICH IT IS ADVISABLE TO SWITCH ON ALL-WHEEL DRIVE (F– COEFFICIENT OF FRICTION)

Conditions of movement	Load of vehicle and trailer	Slipping		Weight of towed trailer, kg	
		KAMAZ – 4350	KAMAZ – 5350	KAMAZ – 4350	KAMAZ – 5350
Blacktop F=0.022	0 %	5%	5%	5040	Impractical
	50 %				
	100 %				
Macadam road F=0.032	0 %			1500	9250
	50 %			1000	9000
	100 %			0	8000
Rolled snow F=0.035	0 %			Expedient at any weight	7750
	50 %				7000
	100 %				5750
Soil road F=0.045	0 %				3750
	50 %				2000
	100 %				0

Experimental study of fuel efficiency of the multi-purpose wheeled vehicle of the type 4x4 (KAMAZ-4350), the type 6X6 (KAMAZ-5350), and the type 8x8 (KAMAZ-6350) with simulation of maximum weight of trailer (4, 6, and 10 tons respectively) when driving on asphalt road with all-wheel drive front axles and disconnected front bridges has showed that for uniform motion, the vehicles with disconnected front axles have the best fuel economy (Fig. 5) [1]. The reduction of the fuel consumption is 5-7% in the transition from all-wheel drive scheme to no all-wheel drive scheme.

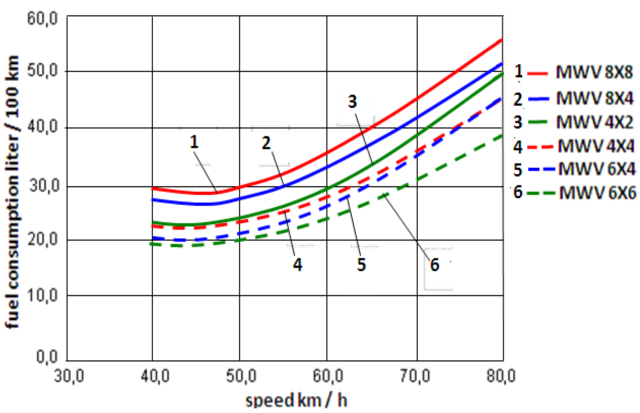

Fig. 5. Fuel characteristics of steady motion of the vehicle KAMAZ with various types of drive

D. Method of limiting excessive action

The essence of the method of limiting excessive action is to reduce the excess capacity of power unit, which cannot be realized on drive wheels of multi-purpose wheeled vehicle because of coupling properties by reducing of fuel supply or the application of braking torque to the slipping wheels.

Effectiveness of the method of limited excessive action was based on a model taking specific of functioning of the brake actuator and the design features of a manual transmission with differential mechanisms into account. Coefficient of slowdown is proposed as a parameter that characterizes the distribution of torque among drive wheels by applying braking torque to the slipping wheels. This coefficient is calculated by the following expression [5]:

$$k_n = M_m / M_{\varphi}, \tag{2}$$

Here M_m is braking torque; M_{φ} is the torque implemented on the wheel according to tire traction.

The degree of braking should be restricted on the basis of the conditions:

- lack of slipping on the surface of the wheel with the worst traction [5]:

$$0 k_n \le \frac{M_{\kappa} - J \cdot \left(\frac{a(1+\delta)}{r_{\kappa o}} + \frac{\upsilon}{r_{\kappa o}} \cdot \frac{d\delta}{dt} \right) - R_{z1} \varphi_1 r_{\kappa o}}{R_{z1} r_{\kappa o} \left(\varphi_1 + f_o \right)}; \tag{3}$$

- full usage of the tire traction on non-slipping wheel [5]:

$$k_n \le \frac{R_{z2} \varphi_2 r_{\kappa o} - R_{z1} \varphi_1 r_{\kappa o}}{R_{z1} r_{\kappa o} (\varphi_1 + f_o)}; \tag{4}$$

- providing of stable movement of multi-purpose wheeled vehicle in conditions of different traction of drive wheels with the bearing surface [5]:

$$k_n = \frac{\pm \sqrt{\left[\varphi_1 (1 - k\delta) R_z + A(1 + C)\right]^2 - D\left[A^2 D + 2\varphi_1 (1 - k\delta) R_z A - R_z (\varphi_2 - \varphi_1)\right]} - \varphi_1 (1 - k\delta) R_z + A(1 + C)}{\left[\varphi_1 (1 - k\delta) + f_o\right] R_z D},$$

here M_K is the torque which is given to semi axis; J is moment of inertia of the wheel; υ is velocity of the multi-purpose wheeled vehicle; a is acceleration of the vehicle; r_{KO} is radius of the free-rolling of the wheel; R_{Z1} is vertical reaction on slipping wheel; R_{Z2} is vertical reaction on no slipping wheel φ_1 is the traction coefficient of slipping wheel with supporting surface; f_0 is the coefficient of rolling resistance; $A = J(\upsilon / r_{ko})^2 d\delta / dt$; $C = B / 2L$; $D = (1 + C^2)$; δ is the coefficient of slipping; R_z, B are constant parameters for given type of the wheel.

Fig. 6 shows the dependence of the braking torque applied to the slipping wheels for vehicle UAZ 3151 depending on the coefficient of friction of driving wheels with the supporting surface during acceleration (with constant acceleration) and uniform motion of one of the

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sides on asphaltic concrete stage. Analysis of the data in Fig. 6 shows that the braking torque applied to the slipping wheels is limited on the one hand by exception of the slipping of the wheels on the surface with worse friction, and, on the other hand, by providing of stable movement of the vehicle.

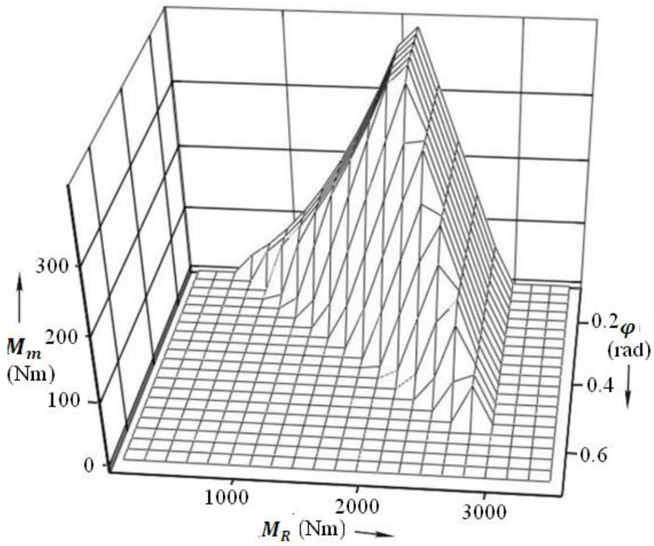

Fig. 6. Graph of braking torque M_m applied to the slipping wheels depending on friction coefficient φ of slipping wheel and supplied torque M_R

III. Conclusions

1. The regularities are identified and engineering methods for implementation of the identified regularities of distribution of power among drive wheels of multi-purpose wheeled vehicle with different types of mechanical transmission are developed, namely: the method of partial solutions; the method of periodic action; the method of limited excessive action; and the method of introducing rigid kinematic connection.

2. In order to apply the method of partial solutions it was developed the methods of determination of rational gear ratio of center differential of multi-purpose wheeled vehicle that provides the required level of mobility of the vehicle. The developed technique includes the stage of collecting of statistical information, the determination of the gear ratio of the center differential in certain driving conditions and with certain types of trailer, the determination of the rational gear ratio for all probable road conditions and types of trailers. On the basis of the developed technique, the recommended ratio for KAMAZ- MWV type 4x4, 6x6 and 8x8 are 1.3, 2.8 and 1.2 respectively. Evaluation of the effectiveness of the method of partial solutions showed that for the multi-purpose wheeled vehicle equipped by center differential with the recommended gear ratios the average speed increases up to 5-9% on solid support surfaces and fuel consumption decreases up to 6-8% in comparison with standard multi-purpose wheeled vehicles.

3. To provide the possibility of introducing of a rigid kinematic connection during the motion of multi-purpose wheeled vehicle, design of differential combined with freewheel was developed. Besides, it was proved the expediency of applying braking torque to the slipping wheels and reducing fuel delivery for preliminary alignment of the angular velocities of the slipping wheels and subsequent lock-axle and cross-axle differentials. It allowed us to increase average speed up to 6-8% on sodden dirt roads and off-road, and reduce fuel consumption up to 10-15% in comparison with standard wheelbase vehicle.

4. To implement the method of periodic action it was proved the expediency of switching off some drive axels. The boundary condition to switch on the axles is the excess slippage loss in running wheels on the power loss in the drive axle. Experimental study of fuel efficiency of the multi-purpose wheeled vehicle when driving on paved road showed that the reduction in fuel consumption is up to 5 - 7% in the transition from the all-wheel drive scheme to no all-wheel drive scheme.

5. It was proved that degree of braking is limited, on the one hand, by exception of slipping of wheels on the surface with the worst cohesion, and on the other hand, by providing of sustainable movement of the multipurpose wheeled vehicle. The method of limiting excessive action by applying braking torque to the slipping wheels, in the presence of a differential connection among drive wheels, provides the increasing of realized acceleration in 1.14-2.2 times, thrust forces on the hook in 1.27-2.96 times, and crossing lifting angles in 2-2.5 times.

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