DEVELOPMENT OF A PREDICTIVE COMPUTATIONAL MODEL FOR TRACTION-DYNAMIC ANALYSIS OF ARTICULATED VEHICLES

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This study examines the traction and dynamic characteristics of an articulated road train in order to develop a predictive mathematical and software modeling system for heavy-duty transport systems. The design, mass, aerodynamic and transmission parameters of the main tractor in combination with the semi-trailer were analyzed and a structured data set for computer modeling was formed. To formalize the sequence of torque transmission from the internal combustion engine to the drive axle, a kinematic scheme of the power unit was developed. Based on the collected parameters, a traction-dynamic mathematical model of motion was formulated in differential form, taking into account the characteristics of engine torque, transmission ratios, rolling resistance, aerodynamic drag and road slope. The proposed model was implemented in the form of a computing core that allows performing time domain modeling and predicting non-stationary operating modes. The interaction between engine characteristics, transmission configuration, and drag was analyzed using numerical integration of control equations. The obtained results made it possible to identify the key factors determining the balance of traction, acceleration capacity and energy efficiency of a road train in various operating conditions. The developed mathematical and software model forms the methodological basis for creating digital twins, computer modeling tools and information forecasting systems aimed at improving fuel efficiency, operational reliability and energy efficiency of articulated heavy-duty vehicles.

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Introduction

The study of traction and dynamic properties of modern truck tractors represents a fundamental research direction in the automotive and transport engineering domain, directly aimed at improving transport efficiency, fuel economy, operational reliability and traffic safety. Over the past decades, long-distance freight transport systems have undergone significant transformation, driven by the continuous growth of cargo flows, increasing traffic intensity on federal highways, and the widespread adoption of articulated vehicles with high payload capacity. In contemporary operating conditions, the gross weight of road trains commonly exceeds 40 tons, which imposes strict requirements on powertrain performance, traction balance and stability of motion [1, 2].

Under these conditions, the adequacy of engine characteristics, transmission configuration and traction reserve becomes a determining factor for ensuring reliable operation of road trains across a wide range of road, climatic and load conditions. Insufficient traction capability leads to reduced average speeds, increased fuel consumption and accelerated wear of drivetrain components, while excessive power margins negatively affect energy efficiency and operating costs. Consequently, traction–dynamic analysis plays a critical role in both the design and operational optimization of heavy-duty vehicles.

Tractor units operating as part of articulated road trains exhibit complex traction and dynamic behavior. Vehicle performance is determined by the interaction of multiple subsystems, including the engine torque characteristic, transmission gear ratios, tire–road adhesion properties, rolling resistance and aerodynamic drag. In contrast to single vehicles, articulated configurations introduce additional complexity related to mass distribution, load transfer to the driving axle and increased aerodynamic resistance. These factors significantly influence acceleration dynamics, gradeability and motion stability.

The dynamic behavior of heavy-duty road trains cannot be adequately evaluated using simplified stationary or quasi-static models. Real-world operating conditions are characterized by non-stationary regimes such as acceleration, deceleration, gear shifting and motion on variable longitudinal gradients. In addition, resistance forces vary dynamically depending on road surface condition, vehicle speed and environmental factors. The resulting distribution of energy between driving forces and resistance forces determines key operational parameters, including acceleration time, maximum achievable speed and overall traction efficiency [3].

The traction characteristics of truck tractors are strongly influenced by both design parameters and operational factors. Engine specific power (expressed in kW/t), the width and structure of the transmission ratio range, and drivetrain losses determine the efficiency of converting fuel energy into useful mechanical work. At the same time, aerodynamic properties and vehicle mass play a decisive role at medium and high speeds, where aerodynamic drag becomes the dominant resistance component. For articulated vehicles equipped with semi-trailers, the drag coefficient typically ranges from 0.55 to 0.70, making aerodynamic optimization and accurate modeling particularly important.

In modern conditions, a prevailing trend in the development of heavy-duty transport systems is the widespread integration of digital modeling and computer-based simulation methods. These methods enable the prediction of traction and dynamic characteristics with a high degree of accuracy prior to conducting time-consuming and costly field tests [4]. Parametric and mathematical models allow researchers and engineers to assess the influence of vehicle mass, aerodynamic properties, transmission parameters and road conditions on traction balance, acceleration dynamics and energy consumption. Simulation-based approaches provide a powerful tool for optimizing drivetrain configuration and ensuring stable vehicle operation under variable loads and operating scenarios, while minimizing energy losses and emissions [5-7, 16-17].

In addition, the rapid development of onboard electronic systems, telematics and data acquisition technologies creates new opportunities for the application of predictive models in real operational environments. Traction–dynamic models implemented in software form can serve as computational cores for digital twins, decision-support systems and energy-efficient driving assistance tools. Such systems enable the transition from reactive to predictive vehicle operation strategies, thereby improving fuel efficiency and operational reliability.

In the context of increasing economic, environmental and technological requirements, improving traction and dynamic characteristics becomes a key factor in the modernization of the national heavy-duty vehicle fleet. The scientific challenge addressed in this study lies in the development of analytical and computational relationships linking traction forces, resistance components and acceleration parameters of articulated vehicles under diverse operating conditions. The purpose of this study is to develop a framework for predictive mathematical and computer-based modeling of traction and energy efficiency of road trains, providing a methodological and informational basis for further integration into digital and electronic transport systems operating under various road and climatic conditions.

Materials and methods

This study is devoted to the KAMAZ-54901-92 mainline tractor (Fig. 1), which is equipped with a KAMAZ-910.12-450 diesel engine.

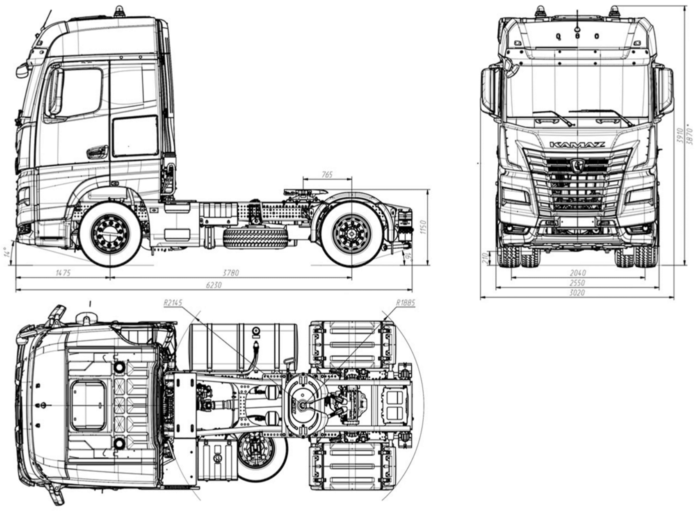

Figure 1. General view drawing of KAMAZ-54901-92

The power unit of the studied vehicle, the KAMAZ-910.12-450 diesel engine, serves as the main source of energy determining the traction and dynamic potential of the KAMAZ-54901-92 tractor [8]. It is a six-cylinder inline diesel engine with turbocharging, direct fuel injection and intercooling. It has been designed to provide high torque at low and medium crankshaft speeds and maintain fuel economy during load fluctuations typical for long-haul transportation.

The maximum effective engine power is 331 kW at 1,900 rpm, and the corresponding maximum torque of 2,060 Nm is reached at 1,300 rpm. It is argued that the torque level under consideration guarantees stable traction characteristics in the most commonly used range of road speeds and gear ratios. The configuration of the torque curve contributes to the efficient use of the transmission range, thereby ensuring the maintenance of an almost constant traction force on several intermediate gears [9, 10]. This is especially true when driving in mixed traffic and on uneven roads, where frequent gear changes are required.

The specific effective fuel consumption of the engine is 183 g/kWh, which corresponds to a fuel density of 0.85 kg/liter. According to the nominal operating conditions, the practical fuel consumption is approximately 60-65 liters/h. This provides a basic basis for determining the energy intensity of the movement and building fuel economy maps in the subsequent stages of the study.

The average effective pressure at maximum torque can be estimated as:

$$p_{me} = \frac{2\pi \cdot M_e}{V_h} \approx 1{,}85\,МПа,$$

It is assumed that the total volume of the engine is 12.0 liters, which is typical for engines of this class. This value confirms the high level of cylinder loading, which corresponds to the performance targets of Euro V–VI diesel units. The mechanical efficiency of the engine at rated load reaches a value of approximately 0.86, while the overall efficiency at rated conditions approaches a value of approximately 0.40. This indicates the optimal conversion of the chemical energy of the fuel into useful mechanical work of the crankshaft [11-13].

The modern power plant of a mainline tractor operates as a cyberphysical system in which torque generation is carried out not only as a result of thermodynamic processes in the cylinders, but also through continuous intelligent data processing from a distributed set of sensors integrated into the electronic architecture of the vehicle. The electronic engine control unit is a real-time computing module connected to the crankshaft position sensor, camshaft position sensor, intake air pressure and temperature sensors, mass air flow sensor, fuel ramp pressure sensor, coolant and exhaust gas temperature sensors, accelerator pedal position sensor, turbocharger boost sensor, and also with an exhaust composition control system. The signals of these sensors are subjected to high-frequency sampling, digital filtering and algorithmic verification for reliability, after which an estimate of the current engine operating mode is formed, characterized by instantaneous load, rotational speed, injection phase, cylinder filling degree and effective air excess coefficient. Information processing is carried out within the framework of built-in control algorithms that implement fuel injection models, temperature and altitude correction, turbocharger geometry control and torque limitation in accordance with permissible mechanical and thermal loads. Unlike the traditional representation of the engine as a static torque source, the intelligent control system generates adaptive output torque based on the current state of the transmission, road resistance and driver commands, ensuring the coordination of energy flows between the power unit and the moving mass of the train. Information is transmitted between electronic units via a high-speed CAN bus, which ensures synchronization of the engine control unit, transmission control unit, traction control system and stabilization modules, forming a single distributed computing environment. Within the framework of this architecture, data on engine speed, current torque, boost pressure, fuel consumption and temperature conditions are available for subsequent integration into telematics modules and external information systems, which allows for a continuous flow of operational parameters into the digital twin of the vehicle. The integration of the computational core of the traction-dynamic model with real telematics data flows ensures the transition from a priori modeling to adaptive forecasting, in which the parameters of motion resistance, coefficient of adhesion and energy efficiency are refined based on current operational measurements. When the road profile or load dynamics change, the engine control system automatically adjusts the duration and phase of fuel injection, limits or increases the supply in accordance with the transmission and clutch protection algorithm, and also interacts with the gearbox control module to optimize the timing of gear shifting. Thus, a closed control loop is formed, in which sensory measurements are transformed into control actions that directly affect the longitudinal dynamics of the train, and the power plant itself becomes an active intelligent element of the transport system [14]. The inclusion of electronic engine control dynamics in the structure of the traction-dynamic model makes it possible to take into account the inertia of the fuel system, turbocharging delays, temperature restrictions and adaptive protection algorithms, which significantly increases the accuracy of predicting transient conditions, especially during acceleration, uphill movement and operation under variable load. Collectively, the described sensor architecture (Fig. 2), computing modules and network protocols form the basis of an intelligent power plant control system that provides not only optimal conversion of chemical fuel energy into mechanical operation, but also the ability to integrate into predictive information and control systems aimed at improving energy efficiency, operational reliability and stability of heavy articulated vehicles in the digital transformation of the transport industry.

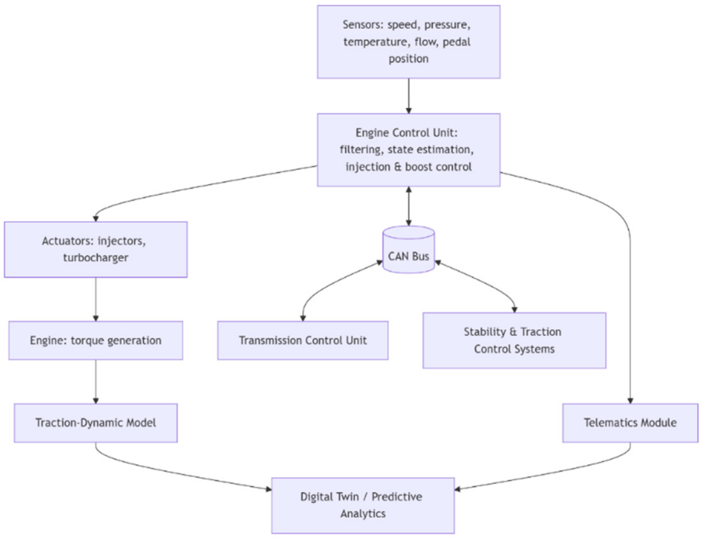

Figure 2. Architecture of the intelligent internal combustion engine system

In the context of the traction–dynamic model, the torque characteristics of the engine are defined as the available traction force on the drive wheels in accordance with the following equation:

$$P_t = \frac{M_e \cdot \eta_{tr}}{r_{st} \cdot U_{tr}},$$

where $n_{tr} = 0.902$ is the transmission efficiency, $r_{st} = 0.74$ m is the static radius of the wheel, and u_{tr} is the total transmission ratio. For example, in first gear ($U_{tr} = 37.997$) and at maximum torque ($m_e = 2060$ Nm), the traction force on the drive wheels reaches ≈ 66.7 kN; in sixth gear ($u_{tr} = 10.388$), this value decreases to ≈ 24.4 kN, which illustrates the expected inverse proportionality between an increase in torque and an increase in the rotation speed. output speed.

The inertia of the engine, characterized by a reduced moment of inertia $J_e = 1.6$ kg m^2, is a key parameter in the analysis of transients, affecting acceleration dynamics and response time when shifting gears. In low gears, inertia helps maintain rotational stability, while in high gears it limits the rate of torque increase, which is especially important when accelerating or climbing a slope [15].

The Tonar T3-13 semi-trailer (Fig. 2) in combination with the KAMAZ-54901-92 mainline tractor is a standard three-axle truck cargo platform designed for long-distance cargo transportation under heavy load conditions. The structural configuration and weight distribution parameters of a vehicle directly affect its traction and dynamic characteristics, affecting axle load, braking stability, aerodynamic drag and rolling resistance.

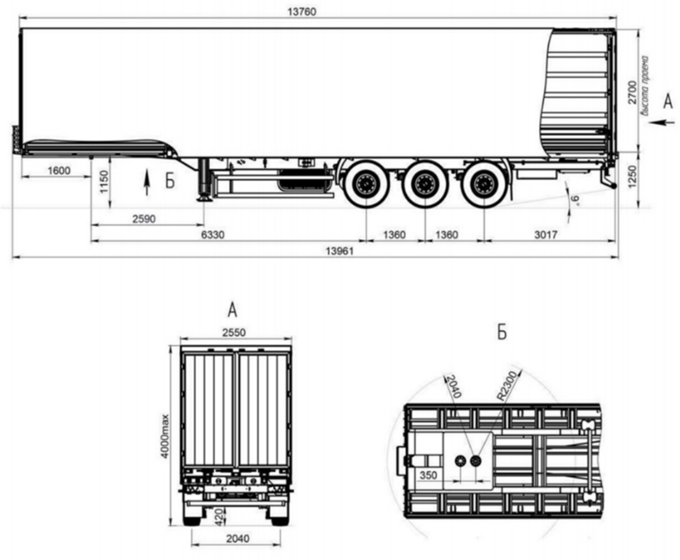

Figure 3. Dimensional drawing of Tonar T3-13

The curb weight of the semi-trailer is 7,300 kg, and the gross weight is 35,600 kg, which provides a load capacity of about 28,000 kg. In the loaded state, the three-axle trolley evenly distributes the total mass between the axles, thereby maintaining the stability of the vehicle both in linear motion and during acceleration or deceleration. When empty, the semi-trailer operates with two touching axles (reduced configuration), which reduces rolling resistance and tire wear. The single-wheel configuration on each axle provides a balance between load capacity and mass efficiency, while maintaining acceptable resistance to lateral skidding on curved paths.

The T3-13 tonar is 13.96 meters long, 2.55 meters wide, and 4.00 meters high. These measurements, which are of great importance in the field of aerodynamics, lead to an increase in the frontal area, which directly affects the overall aerodynamic drag of an articulated road train. The track width is 2.04 m. and the optimized rigidity of the frame ensures sufficient torsional rigidity, thereby minimizing load fluctuations at high speeds. The semi-trailer is connected by means of a coupling device located on the tractor frame at an optimal distance, so that the total length of the road train is 16.65 m, and the total area of the front edge F_a is 6.94 m2.

The aerodynamic characteristics of the T3-13 Tonar are represented by the shape coefficient Ao = 0.85 and the drag coefficient K = 0.59 $N\cdot s^2/m^4$. At a cruising speed of v = 25 m/s (approximately 90 km/h), the semi-trailer accounts for about 40-45% of the total aerodynamic drag of the road train, which is equivalent to an additional drag of about 900-1000 N. This level of drag depends not only on the geometric proportions, but also on the quality of the surface, the blowing of the bottom of the body and the presence of turbulence at the rear.

From the point of view of traction analysis, a semi-trailer acts as a passive load with variable mass characteristics, primarily affecting overall movement resistance due to rolling resistance and aerodynamic drag. The coefficient of rolling resistance under various road conditions corresponds to the general system values: 0.02 for dry asphalt, 0.04 for wet asphalt, 0.06 for packed snow and 0.03 for wet ice. At full load (Gc = 35,600 kg), the rolling resistance on dry asphalt is approximately:

$$P_f = f \cdot G \cdot g = 7{,}0\kappa H$$

To determine the total thrust requirement, this component must be added to the drag forces acting on the tractor.

The weight and aerodynamic parameters of a semi-trailer significantly affect the transmission of the longitudinal load between the axles of the tractor. In the coupled state, the vertical load on the fifth wheel is approximately 7.5-8.0 tons, resulting in a load factor on the drive axle of 29.7% for one tractor and 26.1% for the entire road train. This redistribution determines the available coefficient of adhesion and, consequently, the traction potential, especially on surfaces with a low coefficient of friction.

The Tonar T3-13 uses an air suspension with automatic control, which ensures stable axle load under various conditions of cargo transportation. This design minimizes dynamic fluctuations during acceleration and braking, which contributes to uniform tire wear and improved braking performance. The suspension characteristics are selected in such a way as to maintain stability when driving and reduce the vertical acceleration transmitted to the tractor coupling. This is important for the comfort of the driver and to prevent the coupling device from oscillating.

At this stage of the study, the semi-trailer is considered as a rigid inertial subsystem within the framework of the traction-dynamic model. It provides constant drag proportional to its mass and aerodynamic properties. Subsequent stages of research will make it possible to expand the model to include the elastic and damping parameters of the coupling device, the dynamic interaction between the tractor and the semi-trailer, as well as the oscillatory effects caused by the roughness of the road profile. This will allow for a more detailed assessment of the stability of the articulated system, braking performance and fuel economy in real-world operating conditions.

Results and discussion

At this stage of the research, a basic data set was formed for further traction and dynamic modeling of the KAMAZ–54901-92 tractor in combination with the Tonar T3-13 semi-trailer.

The purpose of the data set formation is to ensure the formation of a database for further analytical refinement, including consideration of dynamic resistances, gradient effects and transient operating modes. The selected parameters describe the mass, size, aerodynamic, propulsion and transmission characteristics of the vehicle system specified in the initial description of measurements and technical characteristics.

Table 1

Initial data for the study of traction and dynamic characteristics using the example of a KAMAZ tractor combination-54901-92 + Tonar T3-13 trailer

Parameter	Symbol / Unit of measurement	Meaning	Description / Notes
Model	-	KAMAZ-54901-92	Two-axle mainline tractor (4×2)
Semi-trailer model	-	Tonar T3-13	Three-axle cargo semi-trailer
Curb weight	*Gst*, kg	8400	Without a semi-trailer
Curb weight of semi-trailer	*Gsp*, kg	7300	Empty configuration
Total weight of the semi-trailer	*Gpp*, kg	35600	Fully loaded
Gross weight	*Gpa*, kg	44000	Tractor + loaded semi-trailer
Total length	*La*, m	16.65	Full hinge system
Tractor dimensions (L×B×H)	m	6.25 × 2.55 × 3.98	Length, width, height
Semi-trailer dimensions (L×B×H)	m	13.96 × 2.55 × 4.00	-
Tractor wheelbase	*Lb*, m	3.78	The distance between the axes
Track width	*Ba*, m	2.04	For both tractor and trailer
Axle load distribution (rear)	%	29.7 (tractor), 26.1 (combination)	-
The front part of the tractor	*Ft*, m ^{2}	6.50	-
Frontal area	*Fa*, m ^{2}	6.94	-
Shape coefficient	*Aa*	0.85	For the combination
Drag coefficient	*Koa*, N·s ^{2}/m ^{4}	0.59	For the combination
Engine model	-	KAMAZ-910.12-450	Turbocharged diesel engine
Rated power	*Ne,max*, kVt	331 @ 1900 rpm	Effective power
Maximum torque	*Me,max*, Nm	2060 @ 1300 rpm	-
Specific fuel consumption	*ge*, g/kVth	183	Nominal
Fuel density	*ρt*, kg/l	0.85	Diesel fuel
Equivalent inertia of the engine	*Je*, kg·m ^{2}	1.6	-
Transmission type	-	12-speed manual	Permanent gear box
Gear ratios (1 – 12)	*Ui*	16.68 – 1.00	-
The final gear ratio of the drive	*Ugp*	2.278	-
Total coefficients (1-12)	*Utr*	37.997 – 2.278	-
Transmission efficiency	*ηkp*	0.965	-
Efficiency of the final drive	*ηgp*	0.935	-
Overall transmission efficiency	*ηtr*	0.902	The average value
Tire size	-	R22.5	Standard double tire
Free radius	*rk*, m	0.79	-
Static radius	*rst*, m	0.74	Used in the calculation of thrust
Tire deformation coefficient	λ	0.94	-
Coefficient of clutch safety margin	β	2.5	Wheel slip protection
Rolling resistance coefficients (f)	-	0.02 – 0.06	Dry – ice
Coupling coefficients (φ)	-	0.75 – 0.07	Dry asphalt – wet snow
Single gear shift time	*t3*, s	0.20	To enter dynamic modeling data

The table above shows the basic configuration parameters necessary to start research on thrust–dynamic calculations. Each parameter represents verified input data for subsequent steps, including:

- onstruction of diagrams of the dependence of traction force and speed;
- modeling acceleration characteristics under various road surface conditions;
- valuation of transmission efficiency and power losses;
- Development of digital modeling modules for a complete combination.

This structured data set completes the preparatory analytical stage of the study. At the next stage of the study, the input variables will be used to calculate traction balance curves, determine traction limit zones, and verify the validity of the preliminary model using experimental measurements on test routes.

As part of the study of traction-dynamic properties, a kinematic scheme of the car's power unit was also developed in order to formalize the structure of torque transmission from the internal combustion engine to the drive axles through the gearbox and transmission system. The schematic diagram (Fig. 4) reflects the general configuration of the KAMAZ-54901-92 tractor and corresponds to its actual mechanical structure.

The torque at the engine output is first transmitted to the gearbox, then through the driveshaft to the main gear and the differential, which distribute the torque to the rear drive axle. Each subsystem is presented functionally, demonstrating the mechanical interaction between the engine, transmission, universal joints, main drive and groups of axles.

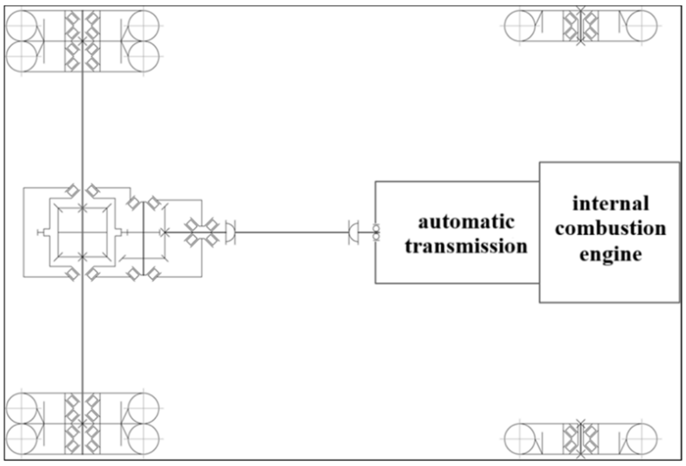

Figure 4. Kinematic transmission diagram of a tractor unit

This scheme is the conceptual basis for determining the main energy losses, determining the overall gear ratio, and determining the components necessary for the design model of thrust dynamics. The configuration corresponds to the 4x2 drive scheme, which is typical for long-haul tractors designed for long-haul transportation.

At the next stage of the study, the emphasis was placed on the development of a predictive mathematical model of the traction–dynamic behavior of an articulated vehicle and on its software implementation for use in computer simulation and information systems. This approach made it possible to move from a static analysis of traction parameters to the forecasting of vehicle motion under non-stationary operating conditions.

The mathematical model of longitudinal motion of the road train was formed on the basis of the traction balance, taking into account the reduced inertial mass of the system and the total resistance to motion. In differential form, the governing equation of motion can be written as:

$$M_{eq}\frac{dv(t)}{dt}=\frac{\eta_{tr}M_e(n(t))u_{tr}}{r_{st}}-\left[Gf\cos\alpha+G\sin\alpha+\frac{1}{2}\rho C_d F_a v^2(t)\right],$$

where $v(t)$ is the vehicle speed, M_{eq} is the equivalent mass of the road train accounting for rotating inertias, $M_e(n)$ is the engine torque as a function of crankshaft speed n, u_{tr} is the total transmission ratio, η_{tr} is the overall transmission efficiency, r_{st} is the static wheel radius, G is the vehicle weight, f is the rolling resistance coefficient, α is the longitudinal road slope angle, ρ is air density, C_d is the aerodynamic drag coefficient, and F_a is the frontal area of the road train.

This formulation explicitly reflects the physical mechanisms governing vehicle motion and enables time-domain simulation of acceleration, deceleration and steady-state regimes. The use of a differential equation provides the basis for numerical integration and makes the model suitable for forecasting applications.

To verify the practical applicability of the developed mathematical formulation, the model was implemented in the form of a computational kernel (Fig. 5). The software realization directly encodes the right-hand side of the governing equation and allows the calculation of instantaneous acceleration for given operating conditions. A fragment of the program code implementing the mathematical model is presented below.

```python
import math

g = 9.80665

def engine_torque(n_rpm):
    # approximation of M_e(n), Nm
    n = max(600.0, min(n_rpm, 2100.0))
    if n <= 1300.0:
        return 1000.0 + (2060.0 - 1000.0) * (n - 600.0) / (1300.0 - 600.0)
    if n <= 1600.0:
        return 2060.0 - 200.0 * (n - 1300.0) / 300.0
    return 1860.0 - 600.0 * (n - 1600.0) / 500.0

def traction_force(n_rpm, u_tr, eta_tr, r_st):
    return (eta_tr * engine_torque(n_rpm) * u_tr) / r_st

def resistance_forces(v, m, f, c_aero, grade_rad):
    F_roll  = m * g * f * math.cos(grade_rad)
    F_grade = m * g * math.sin(grade_rad)
    F_aero  = c_aero * v * v
    return F_roll + F_grade + F_aero

def dv_dt(v, n_rpm, params):
    F_tr = traction_force(n_rpm, params["u_tr"], params["eta_tr"], params["r_st"])
    F_res = resistance_forces(
        v, params["m"], params["f"], params["c_aero"], params["grade_rad"]
    )
    return (F_tr - F_res) / params["m"]
```

Figure 5. A fragment of the program code of the computational core of the mathematical model of a tractor unit

The presented code fragment implements the computational core of the forecasting traction–dynamic model and directly corresponds to the analytical formulation of the governing equation. Numerical integration of this equation makes it possible to obtain time histories of vehicle speed, acceleration and traction reserve for various operating scenarios.

The simulation results demonstrate that the developed model adequately reproduces the transition between resistance-dominated and traction-limited regimes of motion. At low vehicle speeds, the acceleration capability is mainly determined by rolling resistance and the selected transmission ratio, while at cruising speeds aerodynamic drag becomes the dominant factor limiting further acceleration. This behavior is consistent with the physical characteristics of heavy-duty road trains and confirms the validity of the proposed model.

From the standpoint of applied use, the developed mathematical and software model can serve as the core of digital twins, predictive information systems, and decision-support tools for the operation of articulated vehicles. Its modular structure and explicit physical interpretation make it suitable for further extension, including integration with onboard electronic systems, telematics data and adaptive control algorithms.

Conclusion

The analysis confirmed that the traction potential and overall energy efficiency of articulated vehicles are primarily determined by the balance between the characteristics of the engine torque, the choice of transmission ratio and the total drag forces acting on the road train. It has been demonstrated that the aerodynamic configuration and weight distribution of a semi-trailer significantly affect the load transfer to the tractor's drive axle, thereby affecting the available traction, acceleration capacity and longitudinal stability of the vehicle as a whole.

An important result of the research is the transition from descriptive traction analysis to the formation of a predictive mathematical model of longitudinal motion implemented as a computational core. The developed differential formula of traction–dynamic balance and its software implementation confirm the possibility of modeling non-stationary modes of operation in the time domain, including acceleration at various road slopes, surface condition and load.

The results obtained at this stage represent not only a structured set of verified source data, but also a methodological and computational basis for the development of digital tools for analyzing and predicting vehicle characteristics. The implemented model creates prerequisites for numerical integration, scenario-based modeling, and calculation of key performance indicators, including thrust reserve, acceleration dynamics, and drag zones. This allows the model to be directly integrated into computer simulation environments, digital counterparts, and decision support information systems.

Future research is expected to expand and validate the developed model, including the inclusion of detailed engine maps, consideration of rotational inertia and elastic properties of the clutch system, as well as experimental verification in changing road and climatic conditions. Special attention will be paid to the integration of the computing core with on-board electronic systems and telematics data, which will make it possible to predict traction and energy parameters in almost real time.

In general, this work provides a scientific, methodological, and software-oriented framework for creating advanced forecasting and information systems aimed at improving energy efficiency, operational reliability, and technological competitiveness of articulated cargo vehicles. The proposed approach supports the strategic goals of modernization, sustainable development and technological sovereignty of the national automotive industry, especially in the context of long-distance freight transportation.

Appreciation

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References

[1] D. Yu. Malakhov, A. V. Vasiliev, D. S. Taldykin, “Modeling the dynamics of an amphibious auger-rotor platform moving on land,” *DSPA: Issues of Application of Digital Signal Processing*. 2025. Vol. 15, No. 3, p. 50-55.

[2] A. A. Akulov, V. S. Ershov, D. A. Kalintsev, D. S. Taldykin, “Process management in industry and logistics: increasing efficiency and productivity,” *XIV All-Russian Conference on Control Problems: Collection of Scientific Papers*, Moscow, June 17-20, 2024. Moscow: V.A. Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, 2024, pp. 1823-1829.

[3] N. S. Zakharov, V. V. Popcov, N. O. Sapozhenkov, “Adjusting the Maintenance Frequency of Tractor Unit Brake Systems,” *Scientific and Technical Bulletin of the Volga Region*. 2022. No. 11, pp. 55-57.

[4] S. D. Shepelev, A. V. Kletsov, K. E. Gerl, “Performance of Tractor Units in Intercity Transport,” *Transport Planning and Modeling: Proceedings of the International Scientific and Practical Conference*, St. Petersburg, May 26-27, 2016 / St. Petersburg State University of Architecture and Civil Engineering; Association of Transport Engineers. Saint Petersburg: Saint Petersburg State University of Architecture and Civil Engineering, 2016, pp. 82-85.

[5] M. Yu. Karelina, A. V. Podgorny, V. V. Filatov, D. S. Taldykin, “Relevance of Developing a Method for Assessing the Efficiency of Buses Based on a Set of Technical and Commercial Operation Indicators,” *Transport Business of Russia*. 2024. No. 3, pp. 257-260.

[6] N. S. Zakharov, M. V. Nemkov, V. M. Nemkov, “Methodology for Selecting the Brand Composition of Tractor Units Using the Integral Coefficient,” *Intelligence. Innovations. Investments*. 2021. No. 6, pp. 88-95. DOI 10.25198/2077-7175-2021-6-88.

[7] M. Yu. Karelina, A. V. Terentyev, S. D. Shagunov, “Freight flow management in a transport and logistics system based on infinite logic models,” *Sustainable development of urban transport in the Russian Federation: Collection of scientific articles dedicated to the 95th anniversary of the Research Institute of Automobile Transport*. Moscow: Izdatelstvo "Econ-Inform", 2025, pp. 67-84.

[8] N. V. Soloviev, M. Yu. Karelina, “Information criterion model for assessing production efficiency in various modes of transport,” *Transport technician: education and practice*. 2025. Vol. 6, No. 2, pp. 176-181. DOI 10.46684/2687-1033.2025.2.176-181.

[9] V. I. Poddubny, A. I. Valekzhanin, M. L. Poddubnaya, “Mechanics and mathematical model of a truck tractor with a two-axle semi-trailer,” *Polzunovsky Vestnik*. 2016. No. 1, pp. 43-47.

[10] M. Yu. Karelina, Yu. N. Rizaeva, V. V. Baev et al., “Improving the efficiency of the transport and technological system,” *Transport Business of Russia*. 2024. No. 2, p. 192-196.

[11] N. A. Maslov, “Traction calculation and determination of the parameters of the auxiliary drive of the chassis equipment of a road train tractor,” *Energy and resource-saving technologies and equipment in the road and construction industries: Proceedings of the international scientific and practical conference*, Belgorod, October 17-19, 2019. Belgorod: Belgorod State Technological University named after V.G. Shukhov, 2019, pp. 114-122.

[12] Yu. D. Shevtsov, A. D. Nirov, M. M. Zhuravlev et al., “Creation of an experimental database for the purpose of developing intelligent control systems for internal combustion engines,” *Mechanics, equipment, materials and technologies: Electronic collection of scientific articles based on the materials of the international scientific and practical conference*, Krasnodar, November 29-30, 2022. Krasnodar: PrintTerra LLC, 2022, pp. 1014-1019.

[13] Yu. D. Shevtsov, A. D. Nirov, L. N. Dudnik, M. M. Zhuravlev, “Study of the heat balance of internal combustion engines for the development of intelligent control systems in vehicle engines,” *Electronic online polythematic journal "Scientific works of KubSTU"*. 2023. No. 6, pp. 63-77.

[14] A. Yu. Rodichev, K. K. Nastepanin, I. V. Rodicheva, K. V. Vasiliev, “Intelligent system for diagnosing the state of vehicle systems and units,” *The World of Transport and Technological Machines*. 2022. No. 4-1 (79), pp. 3-12. DOI 10.33979/2073-7432-2022-1 (79) -4-3-12.

[15] N. S. Yankevich, A. I. Antonevich, “Methodology for preventive identification of the technical condition of vehicles of the intelligent transport system,” *Bulletin of the Belarusian-Russian University*. 2025. No. 2 (87), pp. 69-79. DOI 10.24412/2077-8481-2025-2-69-79.

[16] A.P. Buslaev, D.A. Kuchelev, M.V. Yashina, “Dynamical systems and mathematical models of information traffic,” *T-Comm*, 2018, vol. 12, no.3, pp. 22-38.

[17] A.S. Bugaev, A.G. Tatashev, M.V. Yashina, O.S. Lavrov, E.A. Nosov, “Reconstruction of traffic flow dynamics based on deterministic stochastic model and data obtained from intelligent transport systems,” *T-Comm*, 2019, vol. 13, no.10, pp. 35-44.

РАЗРАБОТКА ПРОГНОЗИРУЮЩЕЙ ВЫЧИСЛИТЕЛЬНОЙ МОДЕЛИ ДЛЯ ТЯГОВО-ДИНАМИЧЕСКОГО АНАЛИЗА СОЧЛЕНЕННЫХ АВТОТРАНСПОРТНЫХ СРЕДСТВ

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Аннотация

В данном исследовании рассматриваются тяговые и динамические характеристики сочлененного автопоезда с целью разработки прогностической системы математического и программного моделирования для транспортных систем большой грузоподъемности. Были проанализированы конструктивные, массовые, аэродинамические и трансмиссионные параметры основного тягача в сочетании с полуприцепом и сформирован структурированный набор данных для компьютерного моделирования. Для формализации последовательности передачи крутящего момента от двигателя внутреннего сгорания к ведущему мосту была разработана кинематическая схема силового агрегата. На основе собранных параметров была сформулирована тягово-динамическая математическая модель движения в дифференциальной форме, учитывающая характеристики крутящего момента двигателя, передаточных чисел трансмиссии, сопротивления качению, аэродинамического сопротивления и уклона дороги. Предложенная модель была реализована в виде вычислительного ядра, позволяющего выполнять моделирование во временной области и прогнозировать нестационарные режимы работы. Взаимодействие между характеристиками двигателя, конфигурацией трансмиссии и лобовым сопротивлением было проанализировано с помощью численного интегрирования управляющих уравнений. Полученные результаты позволили выявить ключевые факторы, определяющие баланс тяги, разгонной способности и энергетической эффективности автопоезда в различных условиях эксплуатации. Разработанная математическая и программная модель формирует методологическую основу для создания цифровых двойников, средств компьютерного моделирования и информационных систем прогнозирования, направленных на повышение топливной экономичности, эксплуатационной надежности и энергоэффективности сочлененных большегрузных транспортных средств.

Ключевые слова: *тягово-динамические характеристики, транспортное моделирование, седельные тягачи, эффективность транспортных средств, высокая грузоподъемность, кинематическая схема привода.*

Литература

1. *Малахов Д.Ю., Васильев А.В., Талдыкин Д.С.* Моделирование динамики амфибийной шнекороторной платформы при движении по суше // DSPA: Вопросы применения цифровой обработки сигналов. 2025. Т. 15, № 3. С. 50-55. EDN UODKLQ.
2. *Акулов А.А., Ершов В.С., Калинцев Д.А., Талдыкин Д.С.* Управление процессами в промышленности и логистике: повышение эффективности и производительности // XIV Всероссийское совещание по проблемам управления : сборник научных трудов, Москва, 17-20 июня 2024 г. М.: Институт проблем управления им. В.А. Трапезникова РАН, 2024. С. 1823-1829. EDN FXWJKV.
3. *Захаров Н.С., Попцов В.В., Сапоженков Н.О.* Корректирование периодичности обслуживания тормозной системы седельных тягачей // Научно-технический вестник Поволжья. 2022. № 11. С. 55-57. EDN RNCUXW.
4. *Шепелев С.Д., Клецов А.В., Герль К.Э.* Эксплуатационные показатели седельных тягачей в междугороднем сообщении // Транспортное планирование и моделирование : сборник трудов международной научно-практической конференции, Санкт-Петербург, 26-27 мая 2016 г / Санкт-Петербургский государственный архитектурно-строительный университет; Ассоциация транспортных инженеров. Санкт-Петербург: Санкт-Петербургский государственный архитектурно-строительный университет, 2016. С. 82-85. EDN XXZYDV.
5. *Карелина М.Ю., Подгорный А.В., Филатов В.В., Талдыкин Д.С.* Актуальность разработки метода оценки эффективности автобусов по комплексу показателей технической и коммерческой эксплуатации // Транспортное дело России. 2024. № 3. С. 257-260. EDN UKQSLY.
6. *Захаров Н.С., Немков М.В., Немков В.М.* Методика выбора марочного состава седельных тягачей с использованием интегрального коэффициента // Интеллект. Инновации. Инвестиции. 2021. № 6. С. 88-95. DOI 10.25198/2077-7175-2021-6-88. EDN IYXXOD.
7. *Карелина М.Ю., Терентьев А.В., Шагунов С.Д.* Управление грузопотоками в транспортно-логистической системе на основе моделей бесконечной логики // Устойчивое развитие городского транспорта в Российской Федерации : Сборник научных статей, посвященных 95-летнему юбилею Научно-исследовательского института автомобильного транспорта. М.: ООО Издательство "Экон-Информ", 2025. С. 67-84. EDN TADLOO.
8. *Соловьев Н.В., Карелина М.Ю.* Модель информационного критерия для оценки эффективности производства на различных видах транспорта // Техник транспорта: образование и практика. 2025. Т. 6, № 2. С. 176-181. DOI 10.46684/2687-1033.2025.2.176-181. EDN TYNGCO.
9. *Поддубный В.И., Валекжанин А.И., Поддубная М.Л.* Механико-математическая модель седельного тягача с двухосным полуприцепом // Ползуновский вестник. 2016. № 1. С. 43-47. EDN VVIJZF.
10. *Карелина М.Ю., Ризаева Ю.Н., Баев В.В.* и др. Повышение эффективности работы транспортно-технологической системы // Транспортное дело России. 2024. № 2. С. 192-196. EDN OBGNEP.
11. *Маслов Н.А.* Тяговый расчет и определение параметров вспомогательного привода ходового оборудования седельного тягача автопоезда // Энерго-ресурсосберегающие технологии и оборудование в дорожной и строительной отраслях : Материалы международной научно-практической конференции, Белгород, 17-19 октября 2019 г. Белгород: Белгородский государственный технологический университет им. В.Г. Шухова, 2019. С. 114-122. EDN VLAKRP.
12. *Шевцов Ю.Д., Ниров А.Д., Журавлев М.М.* и др. Создание экспериментальной базы данных с целью разработки интеллектуальных систем управления ДВС // Механика, оборудование, материалы и технологии : Электронный сборник научных статей по материалам международной научно-практической конференции, Краснодар, 29-30 ноября 2022 г. Краснодар: ООО "ПринтТерра", 2022. С. 1014-1019. EDN OPPNWG.
13. *Шевцов Ю.Д., Ниров А.Д., Дудник Л.Н., Журавлев М.М.* Исследование теплового баланса ДВС для разработки интеллектуальных систем управления в двигателях транспортных средств // Электронный сетевой политематический журнал "Научные труды КубГТУ". 2023. № 6. С. 63-77. EDN ACFSKJ.
14. *Родичев А.Ю., Настепанин К.К., Родичева И.В., Васильев К.В.* Интеллектуальная система диагностики состояния систем и агрегатов автомобиля // Мир транспорта и технологических машин. 2022. № 4-1(79). С. 3-12. DOI 10.33979/2073-7432-2022-1(79)-4-3-12. EDN DOGYBH.
15. *Янкевич Н.С., Антоневич А.И.* Методика превентивной идентификации технического состояния автомобилей интеллектуальной транспортной системы // Вестник Белорусско-Российского университета. 2025. № 2(87). С. 69-79. DOI 10.24412/2077-8481-2025-2-69-79. EDN JTNUWP.
16. *Буслаев А.П., Кучелев Д.А., Яшина М.В.* Динамические системы и математические модели трафика информации // T-Comm: Телекоммуникации и транспорт. 2018. Т. 12. № 3. С. 22-38.
17. *Бугаев А.С., Таташев А.Г., Яшина М.В., Лавров О.С., Носов Е.А.* Восстановление динамики транспортного потока на основе детерминированно-стохастической модели и данных с интеллектуально транспортных систем // T-Comm: Телекоммуникации и транспорт. 2019. Т. 13. № 10. С. 35-44.

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