Modeling of the Anti-Slip System Processes in the Wheel-Rail Contact of a New Generation Electric Locomotive

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***Abstract*—The article presents a simulation model of the anti-slip system processes in the wheel-rail contact, taking into account track gradients and operational conditions. The model is implemented in the Dymola environment and includes: 1) the single SubWagon model using Modelica Mechanics Translational; 2) a traction control and speed self-regulation model of the new-generation KZ8A locomotive; 3) a wheel-rail contact model for analyzing slip and slide phenomena; 4) a computer model of the anti-slip system. In constructing the model, the geographical and topographical features of the real Agadyr-Darya railway section were taken into account, simulating the movement of a train composed of one KZ8A locomotive section and 35 freight wagons. To describe the control logic, Harel's finite state machine formalism (Statecharts) was applied, which enabled the reproduction of adhesion characteristics under various frictional conditions of the rail surface. The simulation experiment results demonstrated that the developed model reliably reproduces the behavior of traction rolling stock under real operating conditions. This allowed for the synthesis of an adaptive speed controller that accounts for local adhesion coefficient values and the longitudinal track profile (gradients, resistances). The approaches proposed in this work enable preliminary evaluation of the performance of train control systems on specific railway sections before testing or commissioning, as well as modeling the operation of rolling stock under various operational conditions.**

***Keywords*—railway transport, intelligent system, automated control systems, modeling, anti-slip system, wheel-rail traction, speed auto-regulation**

I. Introduction

At present, the pressing economic necessity to increase the volume of railway transportation in the transport corridors of the Republic of Kazakhstan has prioritized the tasks of increasing the weight and length of trains, as the potential for increasing speed and traffic volume has already been exhausted [1, 2]. The main reasons for this situation are high traffic density, the near-exhaustion of capacity on key routes, the low standardization of rolling stock parameters used in passenger and freight operations, as well as wear of wheels and rails, surface and in-ternal contact fatigue defects, and derailments of rolling stock. In mixed traffic, the greater the difference in speeds between freight and passenger trains, the higher the costs of maintaining the track superstructure become. This negates all the advantages of high-speed traffic. Operational experience has shown that with the current traffic density, the frequency of repairs no longer depends on further reinforcement of rolling stock and track elements (rails, sleepers).

The development strategy of the Joint Stock Company "National Company "Kazakhstan Temir Zholy" (JSC "NC "KTZ") of the Republic of Kazakhstan until 2032 envisions a significant increase in freight and passenger turnover on the railway, through the construction of new and reconstruction of existing mainlines, the renewal of the rolling stock fleet, and the improvement of its utilization performance. The creation of modern and efficient designs for rolling stock and its components plays a crucial role in the successful implementation of the planned goals [3]. The relevance of improving rolling stock designs is reflected in the Concept for the Development of the Transport and Logistics Potential of the Republic of Kazakhstan until 2030, approved by the decree of the Government of the Republic of Kazakhstan on December 30, 2022, No. 1116 [4].

A promising approach to fostering a new high-tech framework in Kazakhstan is the development of

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high-speed railway transport. Additionally, the vast territory connecting the Russian Federation, China, Europe, and Central Asia forms the foundation for the development and growth of the national economy. Kazakh-stan's integration with other countries requires not only the development of interregional transport networks for air, sea, rail, and road transport but also the modernization of transport infrastructure, the advancement of logistics, the implementation of domestic software, and the increase of throughput capacity [5].

As is well known, wheel slip leads to wear on the rail head during wheel-rail contact and is a significant issue [5–8]. The solution is aimed at increasing the efficiency of rolling stock, reducing fuel/energy consumption, and minimizing wheel and rail wear, which together will result in an economic benefit.

At present, the issue of increasing the volume of freight transportation by rail for the Trans-Caspian transport corridor remains relevant. This necessitates a significant increase in the mass of freight wagons, maintaining a dense traffic schedule with maximum utilization of locomotive traction characteristics, and improving the wheel-rail adhesion coefficient at a technical level.

However, to date, there is a high level of wear on the rolling stock and mainline networks, reaching around 70% [4–9]. This, in turn, affects train speeds and the capacity of railway sections, hindering the achievement of the goals set by the Government and JSC "NC "KTZ".

The current fleet of railway transport vehicles, whose resources are nearing the end of their life cycle, was designed based on the previous technological frame-work and does not allow for the modernization of existing rolling stock to achieve targeted indicators for improving the efficiency and cost-effectiveness of freight transport. One of the solutions to the aforementioned problems in modeling is to increase the wheel-rail adhesion coefficient in the rolling stock operating on the mainline network of JSC "NC "KTZ".

The implementation of digital control systems and technologies, including the processes of acceleration and braking, will enable the automation of the entire process, thereby eliminating the human factor and increasing the safety of train operations [10].

The relevance of the research tasks stems from the following programs:

- the "Digital Transformation" program in railway transport [11];
- The Concept for the Development of the Transport and Logistics Potential of the Republic of Kazakhstan until 2030, approved by the Decree of the Government of the Republic of Kazakhstan on December 30, 2022, No. 1116, which addresses the following main approaches to the development of the transport and logistics logistics complex until 2030 [4]:

(1) Quality infrastructure provision for the territories of the republic and transport-logistics connections between them.
(2) Development of transit and multimodal integration, increasing the capacity of international transit transport corridors, logistics terminals, and border crossing points.
(3) Enhancement of the technological, scientific-methodological, and resource support for the infrastructure complex. Further improvement, development, and implementation of means for digitization, automation, regulation, control, and management of traffic.
(4) Increasing the economic efficiency and competitiveness of transport infra-structure entities and carriers.

- Strategic Plan for the Development of the Republic of Kazakhstan until 2025, which outlines the priority areas for eliminating barriers that hinder productivity growth and the tasks for developing transport-logistics and trade infrastructure [12, 13].

Thus, the tasks and objectives of the research align with the strategic goals out-lined in the state strategic and program documents of the Republic of Kazakh-stan and contribute to improving the quality of life for the population and enhancing their comfort.

The objective of this paper is to develop and validate a simulation model of the anti-slip control system for the new-generation KZ8A electric locomotive, enabling adaptive regulation of traction force based on wheel-rail adhesion conditions, track gradients, and real operational scenarios. The model is implemented in the Dymola environment using Harel statecharts (FSM) and serves to evaluate the performance of the anti-slip system in terms of improved energy efficiency and increased throughput of the railway corridor.

One of the key features of the KZ8A electric locomotive, developed for heavy freight operations on Kazakhstan's railway network, is its built-in microprocessor-based traction control system combined with a highly responsive anti-slip system that operates in real time. Unlike systems used in earlier locomotive generations (such as 2TE10 or 2ES6), the ASS of the KZ8A is capable of adaptive traction force redistribution across axles and considers local track gradients (Table I). However, the existing scientific literature lacks an integrated model that captures the behavior of such a system under real operating conditions, reflecting the interaction of all locomotive subsystems.

The anti-slip system implemented in the KZ8A locomotive represents a fundamental evolution in comparison with earlier models. It provides adaptive, real-time control based on dynamic traction and adhesion modeling, topographical data, and state-machine logic (FSM). These features enable more effective traction control, reduced energy losses, and compatibility with digital twin frameworks—which were not possible in older locomotive series used on Kazakhstan's rail network.

TABLE I. COMPARISON OF THE ANTI-SLIP SYSTEM (ASS) OF THE KZ8A LOCOMOTIVE WITH EARLIER MODELS USED IN KAZAKHSTAN

No	Criterion	Older Locomotives (e.g., TE10, VL80, 2TE116)	New Generation Locomotive KZ8A
1	Traction Control Type	Electromechanical/basic microprocessor-based systems	Fully digital, high-speed microprocessor-based control system
2	Anti-Slip Implementation	Reactive response to slip after detection	Predictive and real-time slip prevention and correction
3	Consideration of Track Profile (Gradients)	Not available	Available–traction control adapts to track slopes and elevation
4	Control Algorithm for Anti-Slip	Simple threshold-based logic	Harel Statecharts (FSM)–state-transition logic for adaptive control
5	Integration with Adhesion Model	Absent	Integrated with dynamic wheel-rail adhesion model
6	Adaptation to Track Conditions (oil, moisture, debris)	No	Yes, using real-time variation of adhesion coefficient
7	Digital Twin Compatibility	Not supported	Fully compatible with digital twin modeling in Dymola/Modelica

II. LITERATURE REVIEW AND NOVELTY OF THE PROPOSED MODEL

In recent years, the issues of wheel-rail adhesion assessment and slip prevention have received growing attention, as evidenced by publications in high-impact journals [14–16]. Despite valuable findings, most studies are limited either to the identification of adhesion characteristics [14] or to the implementation of high-level control strategies [16] without reference to actual operating conditions and without comprehensive modeling of the traction subsystem. In contrast to these studies, the present work integrates a physically accurate wheel-rail contact model, route-specific train motion modeling on a real section (Agadyr-Darya), and adaptive control logic based on the Finite State Machine (FSM) formalism. This approach enables higher realism, accuracy, and practical applicability of the simulation results.

Recent studies, such as Ref. [17], demonstrate the use of intelligent methods (FLC, PSO) to search for optimal adhesion conditions. The model proposed in this work implements adaptation at the logic level using FSM, with integration into real infrastructure, thereby expanding its applicability within digital twin frameworks.

Unlike the approach of Gan *et al.* [14], which introduces an adhesion identification method based on the TLBO algorithm, the present model incorporates not only a physical wheel-rail contact model but also a control logic that adapts to track conditions and gradients.

As noted in Ref. [15], monitoring the adhesion coefficient significantly improves control performance. In the proposed model, this concept is extended through direct modeling of the wheelset-rail contact and the inclusion of route-specific adaptive control logic.

Studies based on Model Predictive Control (MPC), such as Ref. [17], offer flexible traction force regulation; however, they do not incorporate a physical slip model or interaction with the real track profile-both of which are implemented in the present research.

Barna and Lewandowski [18] present a classical anti-slip protection architecture developed in Simulink. In contrast, this study proposes a more flexible object-oriented approach in Dymola, integrating contact physics and algorithmic adaptation.

Unlike the majority of international studies such as Refs. [14, 15, 17], which conduct modeling under generalized conditions or on laboratory test benches, the present work is based on a real-world geographical section Agadyr-Darya. The model incorporates a new-generation KZ8A freight electric locomotive, ensuring high practical relevance for the railway industry of Kazakhstan.

One of the key elements of novelty is the implementation of Harel statecharts (FSM) for managing the states of the anti-slip control logic, which has not been reported in previous publications. Furthermore, experimentally obtained adhesion coefficient curves for various rail surface conditions were integrated into the model, significantly improving the accuracy of simulating slipping and sliding phenomena.

Moreover, the use of Dymola/Modelica—a modern object-oriented modeling environment—sets this study apart from most previous research that predominantly relies on MATLAB/Simulink platforms [14, 16, 18, 19]. The use of Modelica.Mechanics.Translational, StateMachine, and Contact libraries ensures physical consistency of the processes and allows for visual representation of the realistic interaction between the train and the track. All model components are integrated into a unified hierarchy covering tractive effort, wheel-rail adhesion, logical state transitions, and an adaptive speed controller.

The work features a physically meaningful adhesion model that includes transient processes of slipping (traction loss) and sliding (braking). Gan *et al.* [14] focus solely on parameter identification, and Fang *et al.* [15] rely on estimation without experimental validation. In contrast, the present model incorporates adhesion curves obtained through experimentation under various rail surface conditions (moisture, contamination, and dry contact), thereby increasing modeling accuracy and applicability.

The development of an adaptive speed controller that accounts for gradient profiles and adhesion conditions is implemented using FSM, providing a logically structured control architecture and robust performance under varying operating modes. Among the reviewed studies, none employs FSMs as a means of defining control logic. Although Moaveni *et al.* [16] utilize fuzzy-MPC and Abouzeid *et al.* [17] apply FLC combined with PSO, these approaches lack path profile adaptation and real-time adhesion feedback.

This work aims to reduce energy consumption, minimize rail and wheel wear, and improve the operational efficiency of a freight train consisting of 35 wagons. Real parameters of the route and the KZ8A electric locomotive were used. Unlike most studies limited to test-bench conditions (e.g., Refs. [15, 17]), this model is practically oriented towards real-world operational effects and the development of a digital twin of the locomotive.

Thus, the proposed model holistically integrates all critical levels of train-infrastructure interaction: physical wheel-rail contact mechanics, tractive dynamics, state-based control logic, and route-specific adaptation. Such comprehensive integration within a single digital environment is not observed in the analyzed literature, confirming the high scientific novelty and practical relevance of the presented research.

III. Train Movement Model

The developed simulation model consists of the following interconnected components:

- Rolling stock: a SubWagon module based on Modelica.Mechanics.Translational, representing vehicle dynamics;
- Wheel-rail contact: a physical interface simulating adhesion, slip, and skid based on experimentally derived adhesion curves;
- Traction and velocity control: an adaptive regulator implemented via Harel statecharts (FSM), computing traction force based on target speed and current acceleration;
- Anti-slip logic: a dynamic evaluator that detects slippage based on differential speeds and accelerations, and adjusts traction force accordingly;
- Integrated rolling stock motion model: interconnection of all components and selection of essential parameters;
- Train movement modeling considering the track profile: gradient and resistance parameters reflecting the real Agadyr-Darya railway segment.

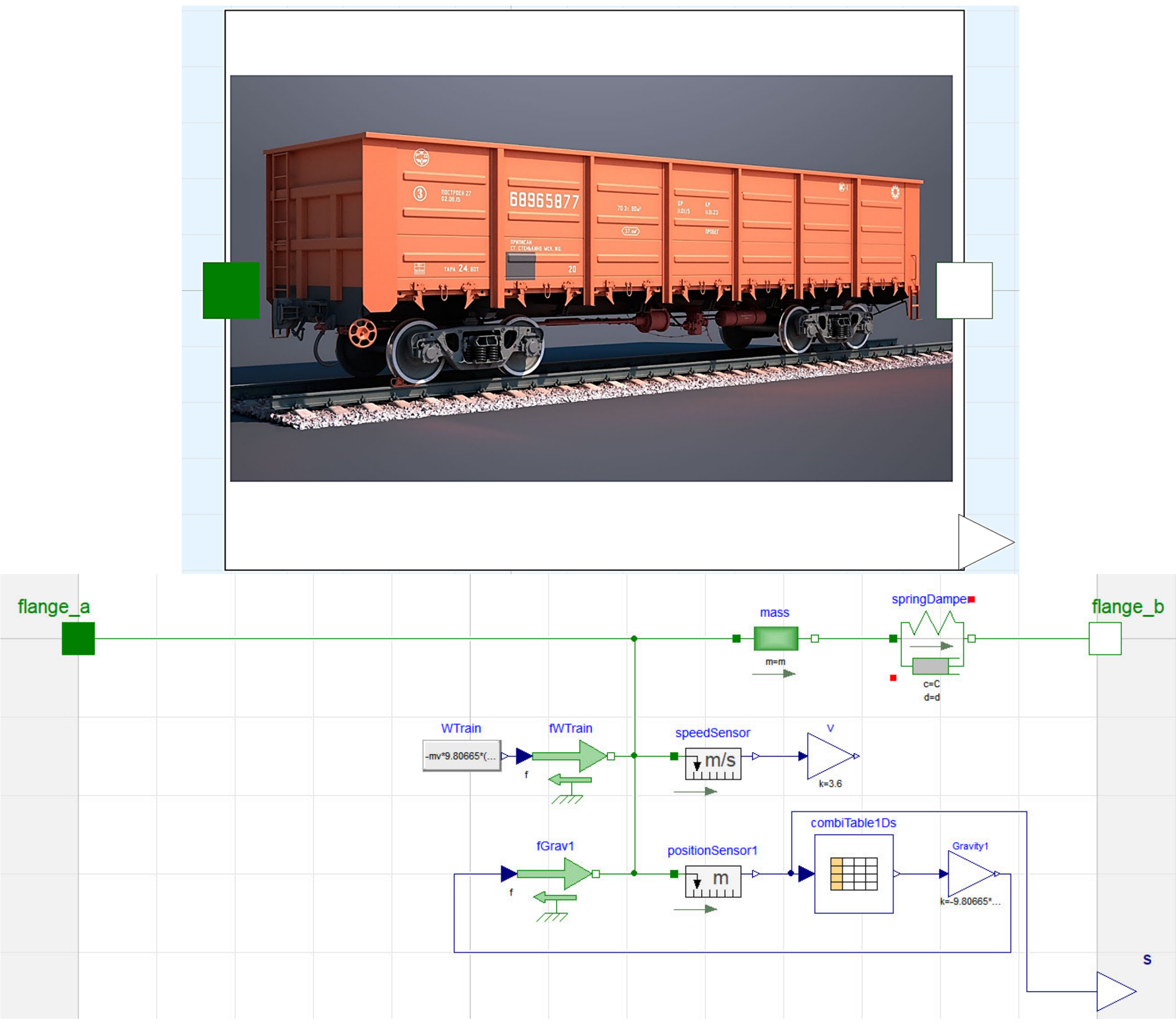
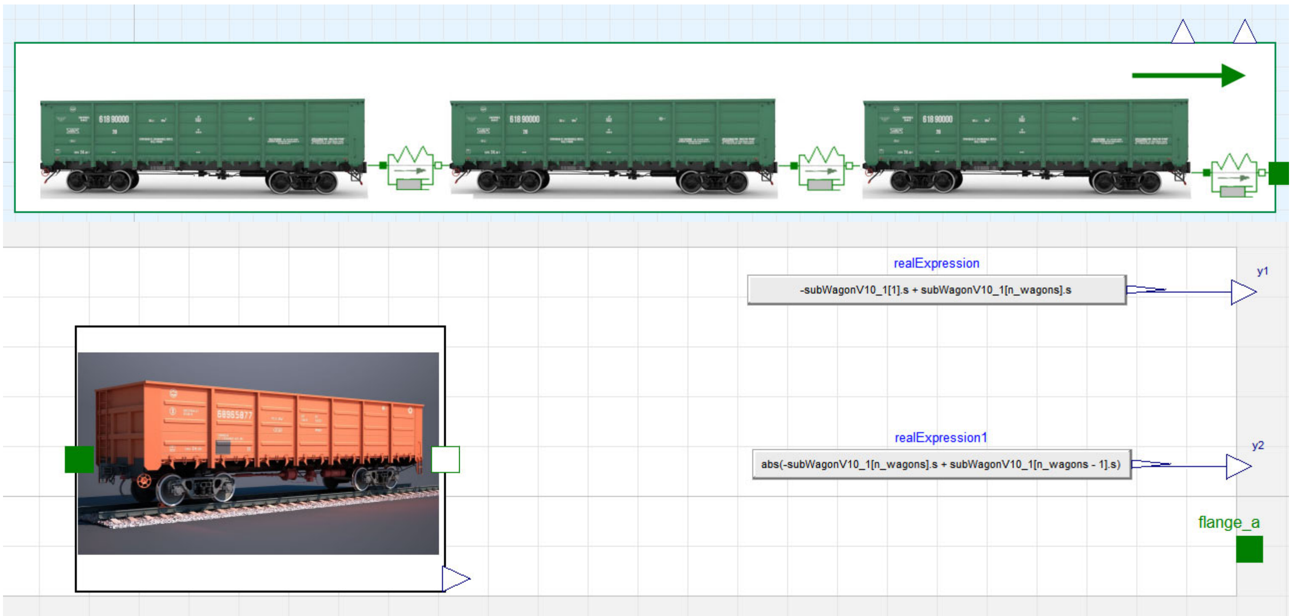


Fig. 1. Wagon movement model.




```
model AllWagonInOne
    parameter Integer n_wagons=10 "Количество вагонов";

    parameter Modelica.Units.SI.Mass m=100000 "Масса вагона";
    parameter Modelica.Units.SI.Distance radius=0.5 "Радиус колеса";
    parameter Real table[:,:]=[0,0; 2000000,0];

    parameter Real L=20 "Длина вагона";

    parameter Real S0=15000 "Начальная координата";
equation
    for i in 2:n_wagons loop
//      connect(subWagonV10_1[i - 1].outlet, subWagonV10_1[i].inlet);
      connect(subWagonV10_1[i - 1].flange_b, subWagonV10_1[i].flange_a);

  end for;
      connect(flange_a, subWagonV10_1[n_wagons].flange_b);


end AllWagonInOne;
```

Fig. 2. The model of freight wagon rolling stock.

The foundation of the comprehensive 1D model is the train movement model, which describes the movement of a consist made up of a locomotive and freight wagons along a calculated track profile with sections of track exhibiting various adhesion conditions (oil, wet rails) [20].

The input data for the model includes:

- a track map, represented as a table—function of track gradient versus coordinates;
- a map of sections with variable adhesion characteristics, represented as a table;
- the number of locomotive sections, length of each section, and mass of each section;
- the number of wagons, length of each wagon, and mass of each wagon;
- speed assignment (function of speed versus coordinates), initial speed of movement, and initial position of the train;
- expression of the primary resistance to motion in accordance with the Traction Calculation Rules (TCR) for train operation.

A model of a single wagon SubWagon, has been developed, as shown in Fig. 1. The Modelica Mechanics Translational library, which describes translational motion, was used to construct the model.

To create a model of rolling stock composed of freight wagons, the model blocks are connected using Modelica code, as illustrated in Fig. 2. The number of wagons is defined as a parameter of the block.

The primary resistance to motion depends on speed and is specified by the force source fWtrain (Fig. 3) in accordance with the TCR.

The resistance to motion due to the gradient also depends on speed and is specified by the force source fGrav (Fig. 4) in accordance with the TCR. When moving uphill, the force has a negative sign; when moving downhill, it is positive. Thus, the resistance due to the gradient is determined separately for each wagon.

The track profile, represented as the slope versus coordinates, is defined using the combiTable1Ds table, as shown in Fig. 5. This figure also illustrates the assignment of the track profile for the Agadyr-Darya section.

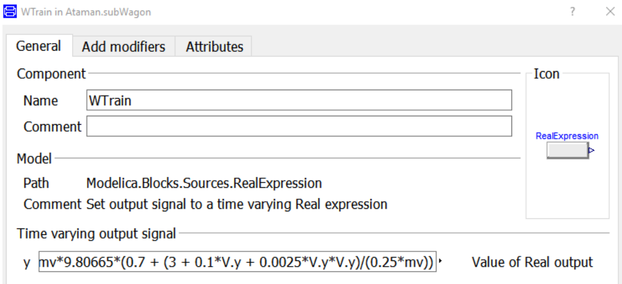


Fig. 3. Primary resistance to wagon movement.

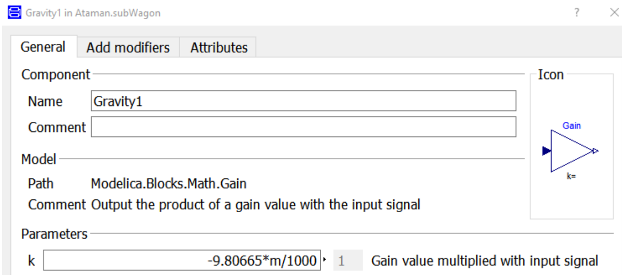


Fig. 4. Resistance to motion due to gradient.

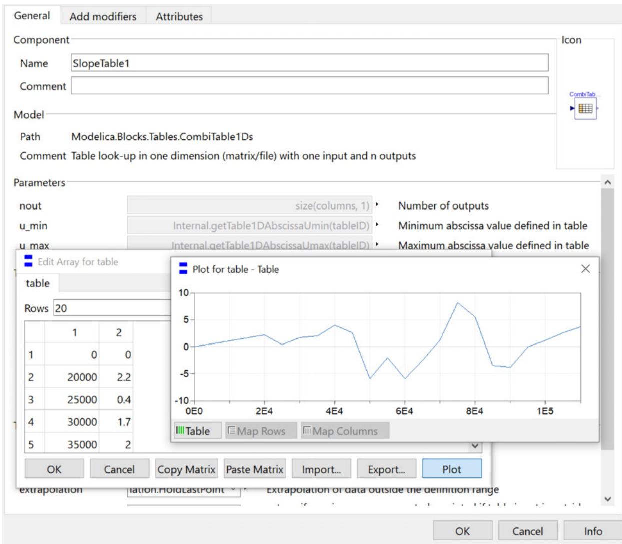


Fig. 5. Track profile assignment (Agadyr-Darya).

IV. Traction Control and Speed Self-Regulation Systems

The KZ8A locomotive control system features a multi-level microprocessor traction control system. The driver has the option to combine the following traction modes:

- select the traction characteristic: continuous, hourly, and half-hour modes;
- choose the control mode: manual, speed self-regulation (cruise control), and automatic driving;
- energy-efficient mode—automatically adjusts the number of traction axles engaged in traction to save energy;
- axle load adjustment mode—allows for the redistribution of traction force de-pending on the load on the axle.

The possible actions of the driver while operating the train are illustrated in Fig. 6.

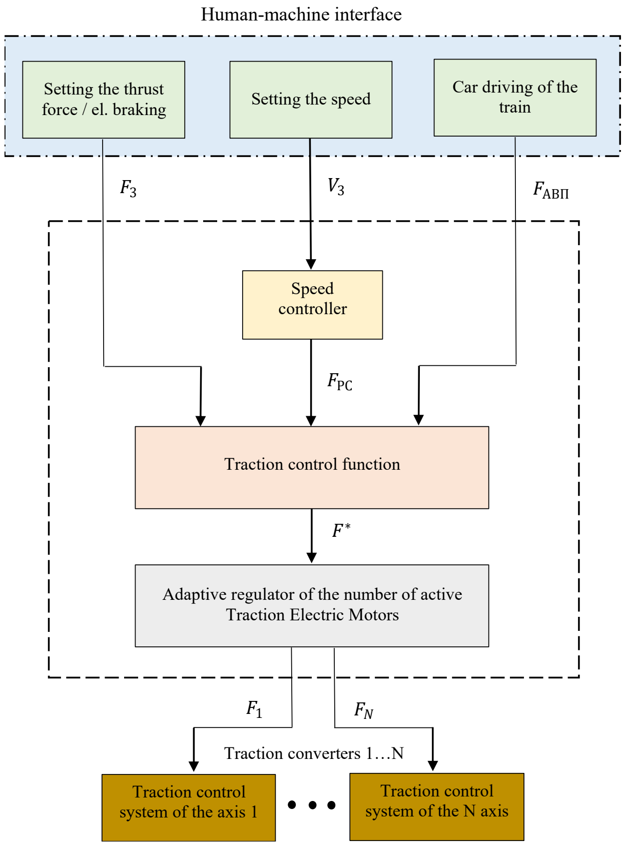


Fig. 6. Structural diagram of the traction control system.

(a) The driver directly sets the traction force FT (manual control mode). The traction force FT is expressed as a percentage of the maximum traction force based on the traction characteristic of the locomotive, taking into account the instantaneous speed, and can vary from 0 to 100%. The setting is made by adjusting the driver's controller handle, and the indication is displayed on the driver's screen [21].

Then, the setting FT is transmitted to the Main Control Unit of the Locomotive and processed using the Traction Control Function block. As the speed changes, the implemented traction force corresponds to the partial traction characteristic, considering the instantaneous speed of the locomotive.

(b) In speed self-regulation mode (cruise control), the driver sets the speed value V_T in *km/h* using the handle. The speed setting V_T is sent to the main control unit of the locomotive in the Speed

Regulator, which adjusts the traction force and electric braking to achieve and maintain the specified speed V_T. This traction force FSC is then transmitted to the Traction Control Function block, and the processes occur as de-scribed above.

The operation of the system depends on the mass of the train, which must be entered into the electronic safety block before the trip.

(c) the driver activates the automatic driving mode, in which traction control occurs automatically in accordance with the electronic mode map and the conditions of movement.

As mentioned above, the Speed Regulator block receives the speed setting V_T and regulates the magnitude of the traction force FSC to maintain the specified speed of movement.

The input variables for the Speed Regulator (SR) are:

- speed setting;
- current speed of movement;
- current acceleration;
- number of locomotive sections;
- number of wagons;
- total mass of the train.

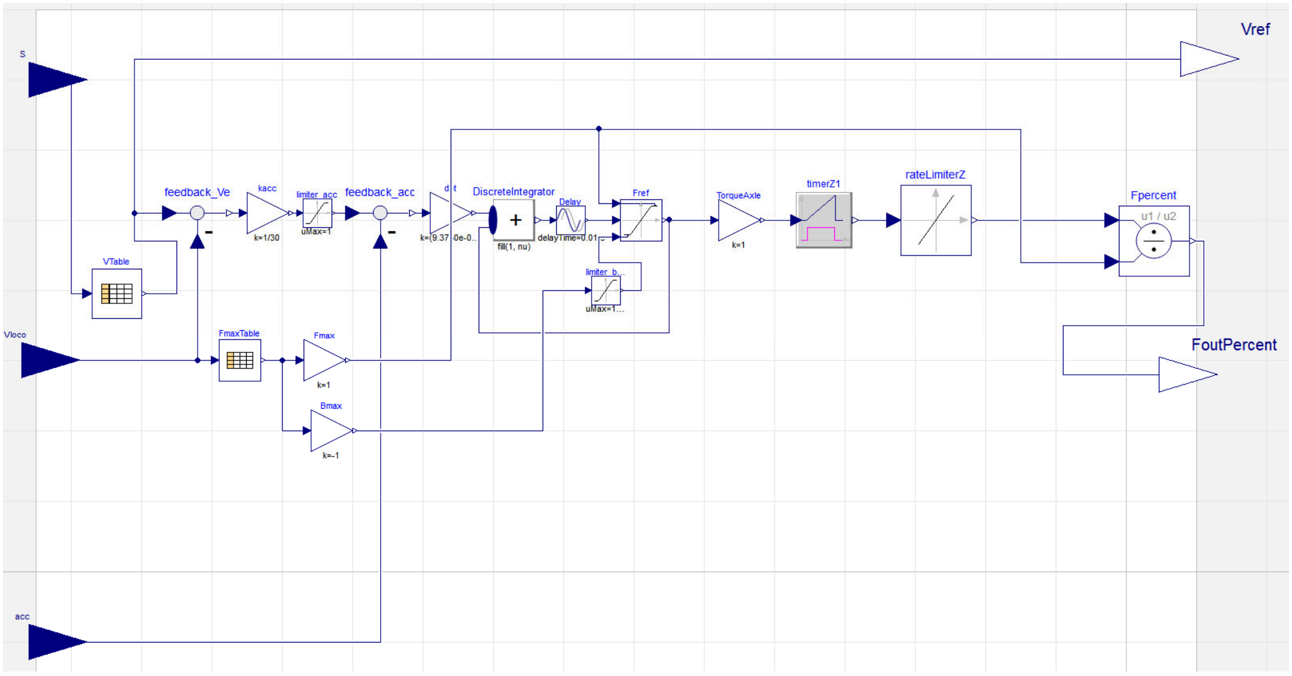


Fig. 7. Model of the speed self-regulation system.

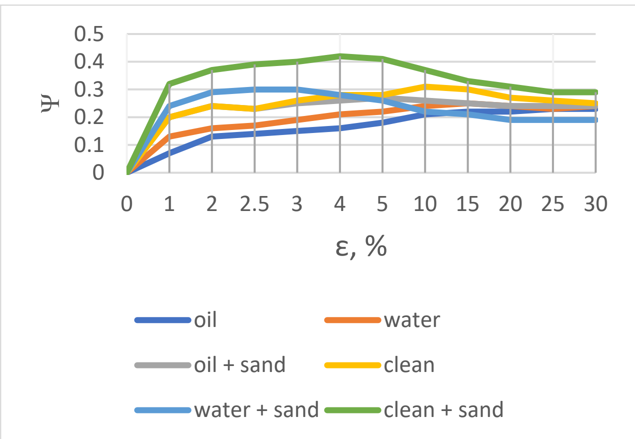


Fig. 8. Adhesion characteristics for various friction conditions of the rail [27, 28].

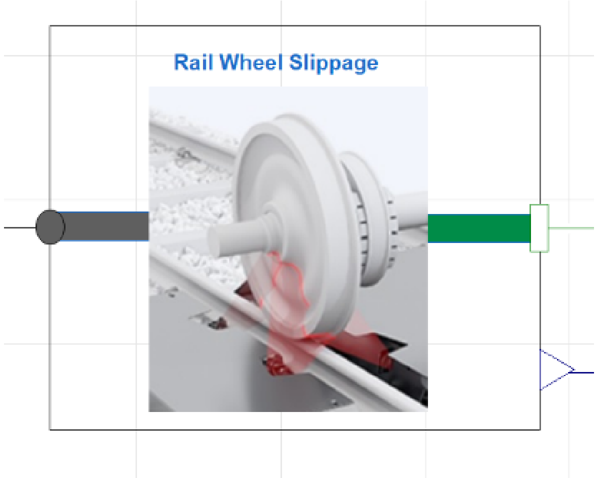
The output variable of the speed regulator is the traction force setting FSC (denoted as F_{ref}), which is sent to the Train module as a control action on the object that calculates the current acceleration, speed, and position of the train. Next, the traction force setting as a percentage of the traction characteristic is converted into the tangential traction force of the locomotive and transmitted to the Traction Control Function (see Fig. 1).

The algorithm of the speed regulator is based on the determination of the acceleration a_i of the train, as the traction force is determined by Eq. (1):

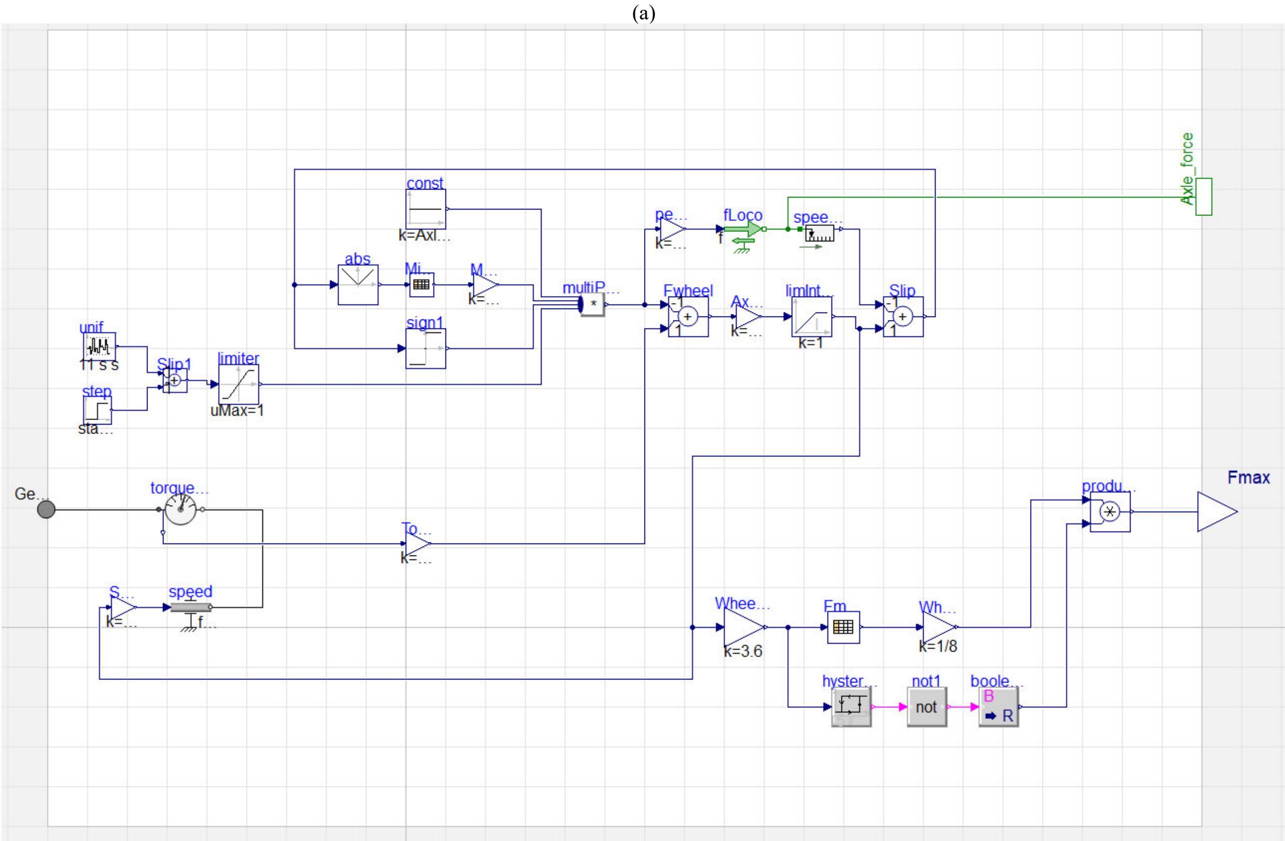
$$F_i = F_{i-1} + \xi\, M\left(a_{ref} - a_i\right) \quad (1)$$

where, F_i—traction force at the current simulation step (time step i), [N]; F_{i-1}—traction force at the previous step $(i-1)$, [N]; ξ—gain coefficient (regulator sensitivity parameter); M—total mass of the train including the locomotive, [kg]; a_i—actual acceleration of the train at time step i, [m/s²]; a_{ref}—reference (permissible) train acceleration, [m/s²]; i—index of the current simulation time step or discrete sampling point.

The model of the speed self-regulation system is shown in Fig. 7. The model was developed in Dymola, using both standard and custom-developed blocks in the Modelica language.



(a)



(b)

Fig. 9. Wheel-rail contact model. (a) wheel-rail slippage; (b) analysis of wheelset slip in traction and braking modes.

A. Processes in the Wheel-Rail Contact

The main indicator of the efficiency of the traction system is the realized tangential traction force. The traction force of the locomotive is generated at the wheel-rail contact due to the torque on the traction motor shaft, transmitted through the gearbox [22, 23]. The model of the processes occurring at the wheel-rail contact can be developed based on specific conditions of the problem [24, 25]. During the traction of the train, to achieve maximum adhesion, it is necessary to maintain the slip speed at the limit of elastic slipping. In the theory of wheel and rail adhesion, the concept of relative slip velocity is used, as defined in Eq. (2):

$$\varepsilon = \frac{V_L - V_W}{V_L} \tag{2}$$

where, V_L—locomotive speed; V_W—linear velocity of the wheel surface $V_W = \omega R$.

The adhesion coefficient depends on the relative slip velocity. Additionally, the adhesion coefficient is influenced by the condition of the wheel and rail, the presence of a third body at the wheel-rail contact (such as sand, oil, water, snow, etc.), and the speed of the train [26]. The experimental characteristic of adhesion at the wheel-rail contact is shown in Fig. 8. Similar results are presented in the works of Minov, Menyshutin, and other authors.

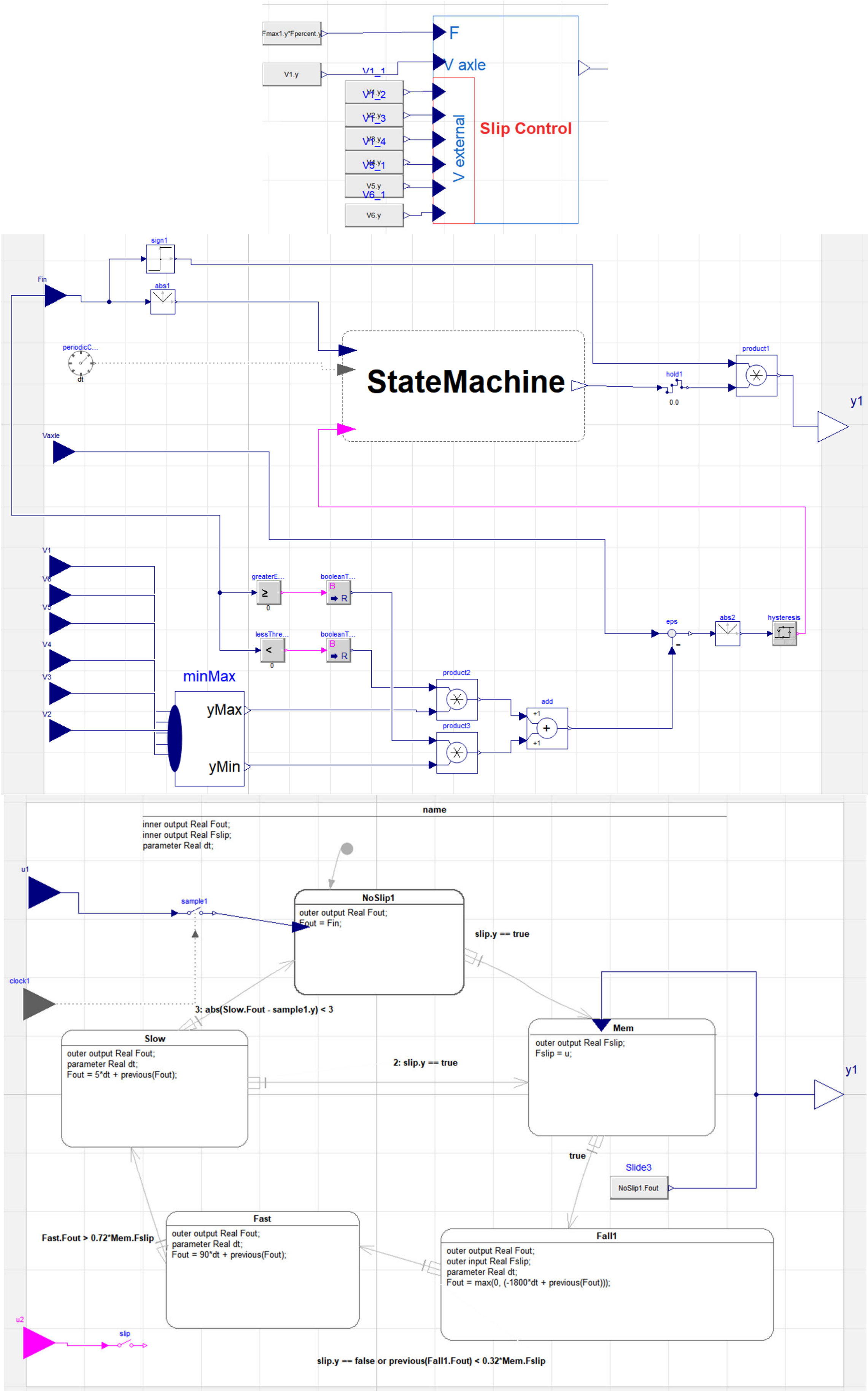


Fig. 10. Model of the anti-slip system block for a single axle.

The characteristics have an extremum at a slip value of $\varepsilon = 3\%$ when using sand. In the zone before the extremum $\varepsilon < 3\%$, elastic slipping occurs, and this section is stable. After passing the extremum, the characteristic decreases, and the wheel enters excessive slipping. Excessive slipping leads to a reduction in the achievable traction force, overheating, and increased wear on the wheelset tread surface.

In the simulation, the curve corresponding to the "clean" rail condition ($\mu \approx 0.3$–0.35) is used, with the capability to dynamically vary the adhesion coefficient along the route.

The wheel-rail contact model (Fig. 9(a) and (b)) is designed for analyzing the wheelset's slipping during traction and skidding during electric braking. This model is intended for the development of an anti-slip system necessary to protect the tread surfaces of wheelsets from damage, prevent loss of traction force, enhance movement safety, and improve the stability of traction and braking properties.

The model is compatible with other Modelica blocks and can be used instead of an ideal wheel without slipping. The input for rotational motion connects to the gearbox, while the output connects to the kinematic scheme of the electric loco-motive (Fig. 9(b)).

B. *Anti-Slip System*

The anti-slip system of the electric train is designed to prevent wheelset slip-ping during traction and sliding during electric braking. This system protects the wheelset surfaces from damage, prevents the loss of traction force, im-proves safety, and ensures the stability of both traction and braking performance [29].

The computer model of the anti-slip system was developed in Dymola and rep-resents a control block that modulates the tractive force based on the readings from the speed sensors of the locomotive's axles. The anti-slip system does not have data on the locomotive's linear speed and relies solely on sensor readings. The traction modulation is adaptive, implemented based on a robust search algorithm, as shown in Fig. 10. The algorithm was developed using Harel's formalism of finite state machines, realized in Modelica StateMachine.

Fig. 10 shows the structure of the anti-slip controller implemented in the object-oriented modeling environment Dymola. The model architecture integrates a FSM, a set of dynamic control laws, and interfaces for traction data processing.

1) *Input signals:*

- F—tractive force generated by the traction motor.
- V_axle—axle (wheel) speed.
- $V\_external$—external reference speed of the locomotive, typically from a navigation block or vehicle body dynamics model.
- $V1\_y \dots V4\_y$—speeds of individual wheelsets used for slip detection.

2) *Control algorithm:*

The core of the regulator is a FSM with three principal states:

- NoSlip—normal adhesion, full tractive effort applied.
- Slide—slip detected, tractive force is rapidly reduced according to an exponential decay.
- Slow—controlled recovery phase with gradual restoration of traction.

The slip value is calculated by comparing the axle speed with the minimum of all wheelset or vehicle body speeds. A hysteresis mechanism is implemented to avoid frequent switching between states due to noise or small disturbances.

3) *Formulas and transitions:*

Transition to the "Slide" state is triggered when the relative slip exceeds a threshold, as expressed in Eq. (3):

$$\text{if}\,(V\_axle - V\_min) \,/\, V\_axle > 0.05 \tag{3}$$

Force reduction logic during the slip phase is defined by Eq. (4):

$$Fout = max(0, -1800 \times dt + previous(Fout)) \tag{4}$$

When traction is restored, the force recovery logic follows Eq. (5):

$$Fout = 5 \times dt + previous(Fout) \tag{5}$$

This modeling approach enables fast suppression of wheel slip and controlled force restoration, avoiding abrupt traction cutoffs and ensuring smoother locomotive behavior on sections with variable adhesion.

V. COMPLEX MODEL OF ROLLING STOCK MOVEMENT

To obtain experimental results from the simulation of freight train movement, the following criteria were selected:

- a train with a total weight of 3500 t;
- for simplification of calculations, a single locomotive section is modeled;
- sand application is disabled;
- the model includes sections of the track with various adhesion conditions (oil, wet rails);
- the operating mode is set for 30 min without load redistribution among the axles;
- the tractive force from the driver's controller is set to 100%;
- weather conditions include light rain;
- both the speed regulation system and the anti-slip system are active.

In Fig. 11, the model of the rolling stock consisting of the KZ8A locomotive and 35 freight cars is presented. This model describes the movement along a specified path, taking into account gradients and including the scenario of the train encountering an oil slick.

Fig. 12 shows the model of a four-axle locomotive section with axle-based traction control. The model comprises four driving axles, each managed by its own anti-slip system. Each block of the anti-slip system receives data on the angular velocity of each axle.

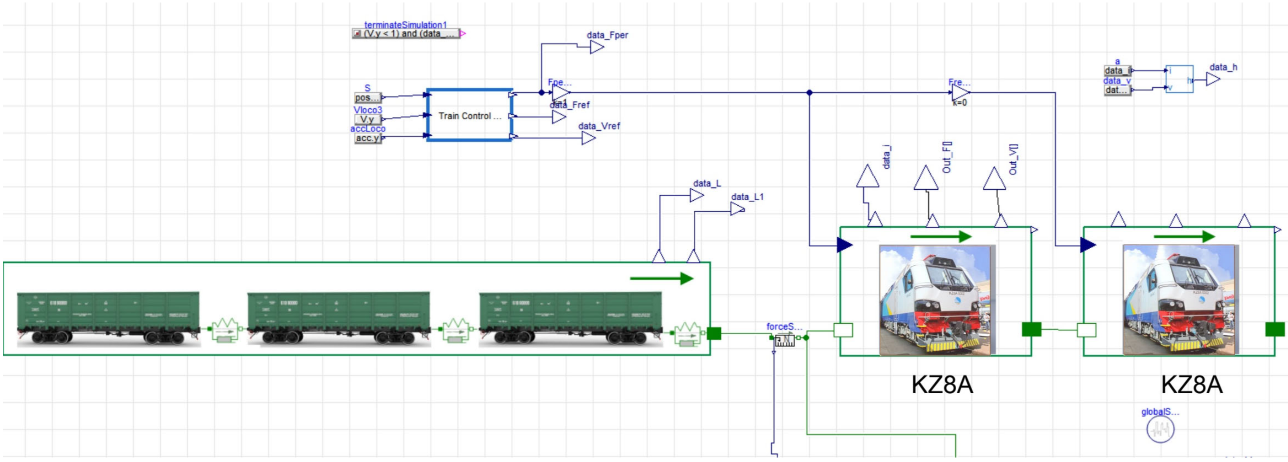


Fig. 11. Model of the rolling stock.

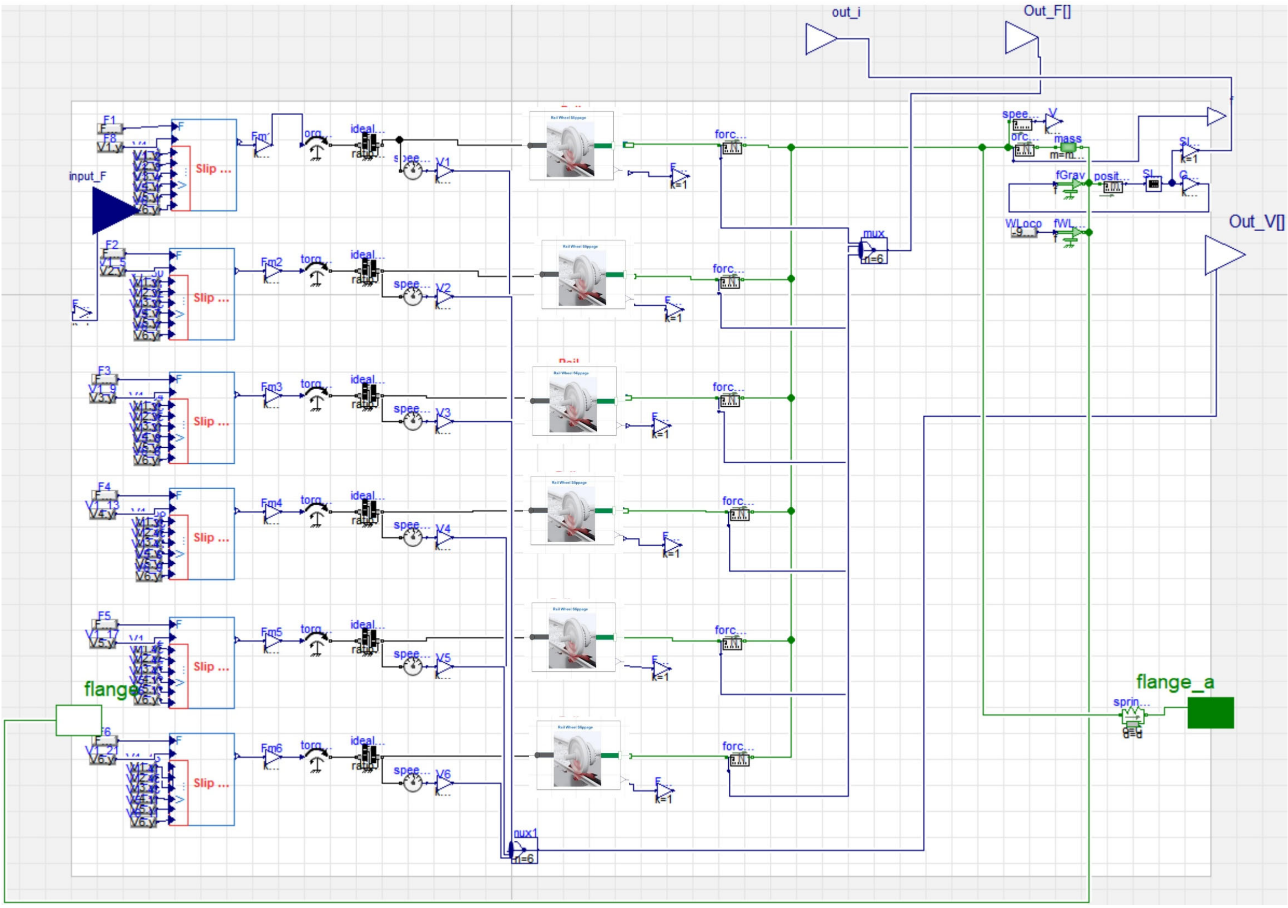


Fig. 12. Model of the locomotive section.

Figs. 13–15 present the results of simulating the movement of the rolling stock in graphical form.

Fig. 13 presents experimental results obtained when the KZ8A locomotive encounters a low-adhesion rail section simulating an oil-contaminated surface. The upper plot shows the divergence between the wheel rotational speed (red line) and the locomotive's translational speed (blue line), indicating the onset of wheel slip. The lower plot illustrates the behavior of the traction force generated by the motor (red line) and the available adhesion force (blue line). Upon entering the contaminated area, the adhesion force drops significantly, while the motor continues to deliver high torque, resulting in loss of traction. This experiment confirms the high sensitivity of the wheel-rail interface to changes in frictional conditions and justifies the implementation of adaptive traction control systems.

Fig. 14 presents the simulation results of train acceleration from standstill on a low-adhesion track section contaminated with oil, under full reference traction force. The top graph shows the behavior of the resultant traction force (%): after the initial buildup, there is a notable fluctuation and reduction in effective traction due to wheel slip. The middle graph illustrates the traction force distribution across individual axles, revealing uneven torque allocation caused by the loss of adhesion. The bottom graph displays the velocity profiles of wheelsets: due to insufficient adhesion, asynchronous acceleration occurs, accompanied by short spikes in the rotational speed of certain wheels.

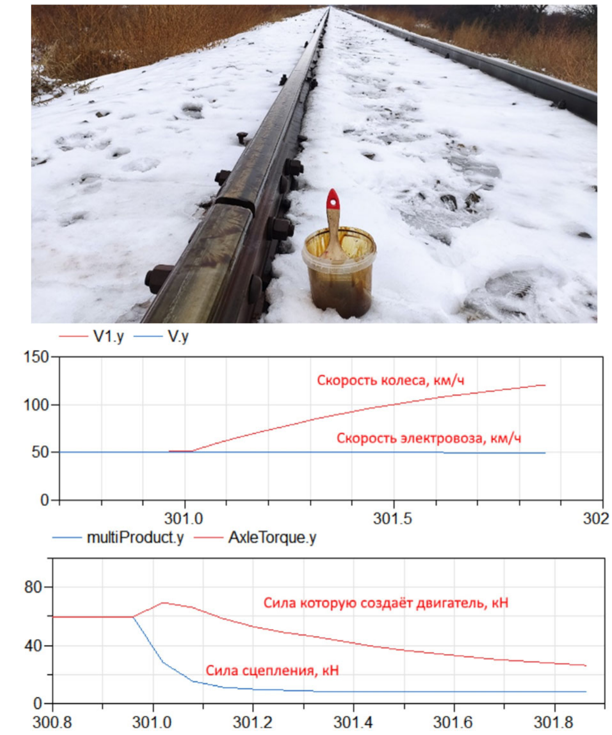


Fig. 13. Experiment results—Impact on an oil patch.

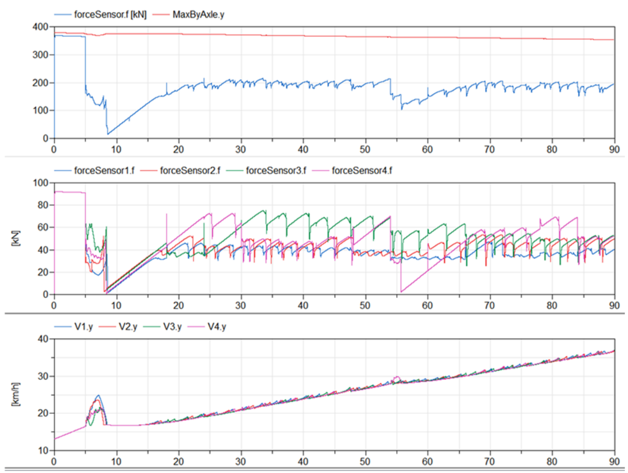


Fig. 14. Experiment results—starting from a standstill on a section of track with oil at full traction setting.

These findings highlight the necessity of adaptive traction control when operating under reduced adhesion conditions and demonstrate the system's vulnerability when applying full traction in such scenarios.

Fig. 15 illustrates the simulation results of a train consisting of one KZ8A locomotive section and 35 freight wagons operating along the Agadyr-Darya section. The top graph shows the elevation profile (in meters) and longitudinal gradient (in ‰) along the route. Clearly visible are ascents and descents, which significantly affect traction demand. The middle graph presents a comparison between the reference (commanded) and actual traction force. In several segments, traction force decreases and even becomes negative, indicating a transition to the regenerative braking mode under deteriorated adhesion conditions. The bottom graph displays the locomotive speed over the route. Fluctuations in speed correspond to the track gradient and reflect the response of the adaptive traction control system.

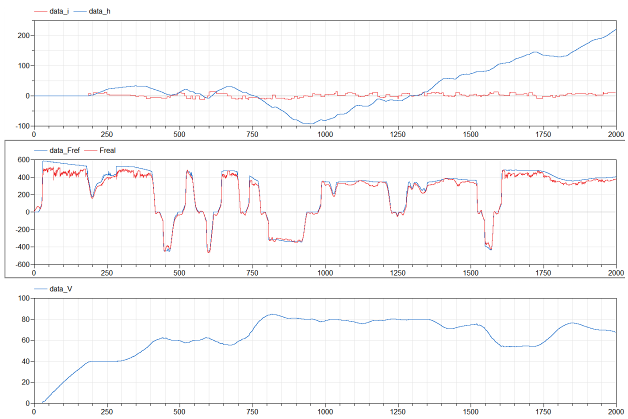


Fig. 15. Simulation results—a composition of one KZ8A section and 35 freight wagons on the Agadyr-Darya section.

The adhesion curve used in the simulation corresponds to a "clean" rail condition ($\mu \approx 0.3$–0.35), with dynamic variation of the adhesion coefficient along the route, taking into account slope changes, axle load, weather conditions, and potential rail contamination.

Even with adhesion coefficients above 0.2, loss of adhesion may still occur, particularly under the following conditions:

- sudden changes in track gradient,
- transitional acceleration or braking modes,
- insufficient adaptation of tractive effort,
- presence of localized surface contamination.

This is clearly demonstrated in the simulation: the top graph shows a discrepancy between the wheelset and locomotive speeds, while the bottom graph shows traction force exceeding the adhesion limit—both indicating a slip onset.

Thus, the model accurately reproduces the behavior of traction rolling stock under real-world conditions, showing that wheel slip can occur even at seemingly "high" adhesion levels (0.25–0.3) when dynamic factors are present.

VI. Discussion

As part of the pilot project, a computer simulation model of the rolling stock was developed, enabling the study of locomotive control systems' performance in various modes. The speed regulation system and the anti-skid system were investigated and verified. The developed model allows for the synthesis of an adaptive speed regulator that considers local characteristics of wheel-rail adhesion as well as the gradients of the railway track.

These engineering studies demonstrate modern methods for creating new algorithms and improving existing control systems. These approaches enable the pretesting of systems on specific sections before the commencement of trials or the operation of the locomotive, as well as simulating the movement of rolling stock under various conditions [30].

1D modeling enables the rapid and efficient development of control algorithms and the selection of optimal system settings prior to conducting field tests.

While direct experimental verification of anti-slip efficiency under real-world KZ8A operation remains challenging, the model has undergone multi-level validation:

(1) Real-world topographical data from the Agadyr-Darya route were incorporated into the simulation to emulate realistic traction-resistance interactions.

(2) The wheel-rail contact block was configured using experimentally obtained adhesion curves for various surface conditions (dry, moist, contaminated, sand-covered), as presented in Fig. 8.

(3) The model's ability to exceed the Rules of Traction Calculation traction limits by 20% without instability or excessive slip acts as an indirect indicator of the model's validity under practical conditions.

Supplementary Economic Insight:

Assuming an average cost of 85,000 KZT per locomotive-hour, a 15% reduction in trip duration (e.g., from 11.8 to 10 hours) due to improved traction would yield:

Savings:

1.8 hours × 85,000 KZT = 153,000 KZT per trip

Additionally, reduced slip/skid cycles extend wheel and rail service life, leading to a 10% increase in maintenance intervals and 5–12% savings in periodic repair costs, based on national maintenance standards.

The modeling and simulation methods employed in the Dymola tool should be widely used in the study of locomotive control systems, as this will reduce development time and minimize the probability of errors.

VII. Conclusion

As a result of the research, a model of a single wagon SubWagon, was developed in Dymola using both standard and custom-designed blocks. To create the model of a freight train, the blocks were interconnected using Modelica code.

The developed wheel-rail contact model is intended for the design of an anti-slip system necessary to protect the contact surfaces of wheel pairs from damage, pre-vent the loss of traction, enhance operational safety, and ensure the stability of traction and braking properties. Experimental characteristics of adhesion have been obtained for various friction conditions of the rail.

The proposed model is compatible with other Modelica blocks and can be used as a substitute for the ideal non-slip wheel. The algorithm has been developed using Harel's formalism of finite state machines, implemented in Modelica StateMachine.

The modeled train consists of one section of the new-generation KZ8A electric locomotive and 35 freight wagons. The results demonstrate that implementing a high-performance anti-slip system enables the locomotive to exceed the conventional traction limitations defined by the Rules of Traction Calculation by more than 20%, which has the following implications:

- Increased train mass for the same track profile;
- Reduction in the number of trips needed to transport the same freight volume;
- Decrease in slip/skid cycles, thereby reducing dynamic stresses;
- Reduction in locomotive-hours by approximately 12–18% for long-distance operations;
- Estimated reduction in wheel and rail wear by 10–15%, based on empirical studies.

Moreover, stabilizing wheel-rail adhesion improves traction drive efficiency and reduces energy losses associated with micro-slips and skids. These factors collectively contribute to operational cost reduction and extend the service life of critical components.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

KS and BS developed the SubWagon model and simulated freight train movement, including topographic data of the Agadyr-Darya section. YB and TC designed the speed autoregulation and wheel-rail contact models in Dymola. DS and LT implemented the traction control model for a single axle. TC the manuscript; all authors contributed to the modeling, analysis, and final approval of the manuscript; all authors had approved the final version.

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