International Journal of Advanced Mechanics and Control Systems

Volume1, Issue 3 2025

Control system for maximum use of adhesive forces of a railway vehicle in a tractive mode

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Research Article

Date of Submission: 16-06-2025 Date of Acceptance: 10-07-2025 Date of Publication: 11-08-2025

Abstract

Because it requires tractive efforts and relies on friction properties in the contact zone between wheels and rails, achieving maximal adhesive forces for a railway vehicle is an extremely challenging procedure. Tractive torques of motors are used to achieve tractive efforts, and their highest levels may result in adverse consequences like skid and slide. These circumstances often arise from a lack of knowledge about friction conditions. The wearing of tractive units and contact bodies is significantly impacted by the negative processes. Because it is extremely difficult to measure a friction coefficient while a vehicle is moving, many current vehicle control systems rely on the influence of a forecast of a friction coefficient between wheels and rails. Using noise spectrum analysis to identify the friction coefficient is one method to do this objective. This noise phenomena has not been thoroughly investigated and examined. In this paper, we propose an observer-based adhesion control system for railway vehicles that enables one to calculate the maximum tractive torque based on the ideal adhesive force between a railway vehicle's wheels (wheel pair) and rails (rail track) based on weight load from a wheel to a rail, friction conditions in the contact zone, a lateral displacement of the wheel set, and wheel sleep. Consequently, it enables the highest adhesion force for actual friction circumstances to drive a railway car in a tractive mode.

Keywords: Control system; Railway vehicle; Adhesive force; Torque; Slip

Introduction

The adhesion process between a rail and a wheel during the mode of realization of tractive efforts determines both the efficient application of power and the energy consumption by railway vehicles. Design adhesion coefficients must be given the appropriate weight in the development of railway vehicles. Real adhesion coefficients, however, deviate significantly from design adhesion coefficients. For locomotives, for instance, the gap might be as much as 740%. It is shown that although we have some reserves, we also have certain expenses related to slide and tractive loss.

The adhesion coefficient is a complicated phenomena. Many eminent scientists have been studying adhesion forces in recent years, including J. Piotrowski, K. Knothe, M. Ertz, O. Polach, H. Chollet, F.D. Fisher, Yu. Luzhnov, A. Golubenko, and others. Adhesion control systems were developed using the research's findings. Nevertheless, we do not now have completely flawless methods that are capable of increasing the adhesion coefficient and making a highly successful realization.

According to a study and analysis of adhesion control systems for railway cars by Frylmark and Johnsson [1], adhesion control for anti-slip control systems may be explained using a number of control schemes that have a lot of similarities. Few of them employ signals other than adhesion and vehicle velocity as inputs. The ways in which these signals are interpreted and processed varies greatly. The findings of this paper show that controllers using fuzzy logic and steepest gradient techniques may get the highest performance.

Using the novel torque command function C(t)100 and a first-order disturbance observer built on the torque feedback control approach, the research [2] suggests an adhesion control system for an electric motor coach.

According to the authors' scientific research, the suggested control strategy increases the electric motor coach's driving wheel torque steadily and reliably even when the adhesion force coefficient varies significantly. However, the study [1] claims that this controller's implementation failed since the suggested techniques need system excitation and the slip curves utilized in [2] lacked a plateau following the peak.

By concentrating on the current of each motor, Watanabe and Yamashita [3] examined the issue of adhesion control, which is used for slip detection without a speed sensor. According to the authors, the behavior of motor current during a slide may be used to infer adhesion force. However, we believe that this method prevents achieving the highest level of adherence.

A control strategy based on modifying the torque command for the motors in accordance with the predicted adhesive forces between wheels and rails is described by Matsumoto et al. [4]. Although we know that the realized and maximum adhesive forces may vary, the paper contains information on how to collect information on realized adhesive forces.

The control system for the Korean high-speed train with induction motor drive, developed by Ryoo et al. [5], enables the use of the maximum adhesive effort and enhances tractive performance and adhesion characteristics. Conventional pattern control and speed difference control serve as the foundation for the suggested anti-slip control system. However, we believe that the applied procedure is not optimal by the maximal adhesion criterion either.

The control system for an electric railway car powered by inverted induction motors is presented by Ohishi et al. [6]. Their early study is continued in this paper. The suggested approach enables accounting for the vibration phenomena of the real bogie and is based on the suggested high-order disturbance observer and sensor-less vector control. The benefit of this scientific endeavor is that actual experimental findings of re-adhesion control utilizing a tested bogie of an electric commuter train validated the simulation that was carried out.

The development of an adhesion control system employing beam model railway adhesion characteristics was investigated by Yamazaki et al. [7]. In this study, simulation was used to get the braking mode control system. One crucial issue is this: how can the beam model for operating cars be made to have the highest coefficient of adhesion? Since it is difficult to measure adhesion force directly, they used a disturbance observer to estimate adhesion force. The relationship between wheel velocity and tractive unit features was used for the observer's proper task. Continuing their research in this area, Yamazaki et al. [8] introduce a braking mode control system based on sliding mode control theory. Compared to the traditional controllers, the suggested solution is more stable.

Regarding the issue of determining the true adhesion coefficient, the study [9] is quite intriguing as the authors suggested using computational techniques and neural network estimates to estimate the friction coefficient. Unfortunately, we were unable to locate any information on the use of the suggested neural network estimate approach in control system design.

Ukrainian researchers developed an adhesion control system that uses noise analysis to forecast the maximum adhesion coefficient [10]. The steepest gradient method-based control system was presented. Regretfully, complete simulation results are not presented in this paper.

Leading businesses and academic institutions that do research in this area have shown that the use of microprocessor systems produces positive outcomes for the management of adhesion processes in tractive and
ways of braking. The creation of adhesion control and adjustment techniques based on information from wheel-rail contact noise diagnostics is one potential answer for this problem.

Adhesive force in wheel–rail contact

The adhesion force is realized on small surfaces of a rail–wheel contact. Many factors have an influence on an adhesion process for those surfaces (environment, pollution, parameters and technical conditions of railway vehicle, track, etc.).
The main theories of wheel–rail interaction consider only the interaction between two bodies. However, in real conditions, a third body is present in the contact. We can see from [11] that the presence of a third body has a different range of thickness from a few micrometers to several dozen micrometers, making contact interaction analysis more complex. Under these conditions, the third body has a major influence on friction and adhesion coefficient in the contact zone.
The friction coefficient can increase or decrease depending on the presence of a third body in a rail–wheel contact. As seen from article [12], the change of contact conditions is possible by means of directions and modification of friction surfaces.
In this case, many experimental researches of friction properties of wheel–rail contact and mathematical modelling have been performed [13–15]. As a result, the regression equation, which describes the optimal process of interaction between a wheel and rail for different friction conditions, was obtained [16–18]. It can be calculated as

$$F = N_a \left(\frac{S}{S_0} \right)^{A_1} / \exp(\pi B) + A_2 \ln(\pi B) + A_3 / (\pi B) + A_4 (\pi B) + A_5 T_2 T_4 / T_7 T_8, \quad (1)$$

where N is the weight load from a wheel to a rail, A_1, A_2, A_3, A_4, A_5 the coefficients of relation, $\vec{S}$ the vector of wheel slip, e the relative slip (%), $B = T_1T_3T_5T_6$; T_1, T_2 the coefficients, which can be changed depending on noise in rail–wheel contact, T_3, T_4 the vertical load coefficients, T_5 the velocity coefficient dependent on the velocity of the locomotive, T_6, T_7 the coefficients, which are dependent on cross-motion of a wheel relative to the rail, and T_8 the coefficient of angle of attack of the wheel.

Relative slip is defined as

$$\text{Л} = \frac{r\text{o}_{wh} - V}{r\text{o}_{wh}} \times 100\%, \quad (2)$$

where o_{wh} is the real angular velocity of a wheel, V the locomotive velocity, and r the radius of wheel. This equation is confirmed with a considerable amount of experimental research. The example of calculation with relation (1) is shown in Fig. 1.

In Eq. (1), the coefficients should be defined depending on the railway vehicle and track design. The friction condition of a rail and wheel is described with the friction coefficient. For the calculation of adhesive force for contact bodies it is necessary to use the maximum friction coefficient m of concrete friction condition, which can be received by means of noise spectrum analysis.

Rolling noise in wheel–rail contact

A large number of research works are being done for the detection and simulation of noise for railway transport at the present time. According to research in [19,20], we have the factors, which have a strong influence on noise creation. The following factors can be split into three (type of braking system and wheel maintenance, rail maintenance categories:

Parameters influencing the noise generation:

- roughness (type of the braking system and wheel maintance, rail maintance);
- contact patch (wheel load, wheel and rail profiles);
- number of wheels;
- wheels and rails defects (wheel flats and etc.);
- train speed, sleeper spacing, and statistical variation of mechanical characteristics of track components.

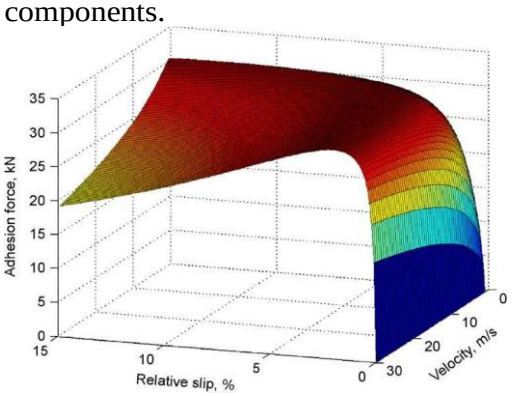


Fig. 1. Calculated dependence of adhesion force F_a from relative slip e, vehicle velocity V for worn wheel and rail profiles of a railway vehicle.

Parameters influencing the track radiation:
J wave propagation (vertical and lateral decay rates, rail pad stiffness and damping loss factor);
J radiation efficiency of track (rail, sleeper, and pad).
Parameters influencing the rolling stock radiation:
J train speed;
J wheel characteristics (diameter, wheel vibration eigenmodes).
These factors were accounted for in the development of models for the prediction of rolling noise (for example, Twins and SFE ACUSRAIL). The modelling process allows the separate components of noise from the wheel, rail and sleeper to be identified. From works describing these models, we can see that they use simplified mathematical models to calculate the wheel–rail interaction. Application of these simplified models for noise calculation does not into account many parameters, which have a big influence on the interaction process in the contact zone. From research described in [21] for automotive transport, we can see that the conditions of surfaces have a big influence on noise level. Similar researches are being done in the field of railway transport. For example, the influence of the roughness of railhead on noise level is described in the work [22]. From this work, we can see that railhead roughness can have significant effects on levels of rolling noise from trains. This can be a major issue locally, as some trains can be 20 dB or noisier on very rough or corrugated rails than on smooth rails. Therefore, we can make an analytic conclusion that the presence of a third body in the contact zone between a wheel and a rail should assist to change the friction coefficient in this contact, which means, furthermore, that the friction coefficient has a big influence on a noise level in the contact zone. Based upon what is written above, it is possible to develop an adhesion control system that allows accounting for the adhesion characteristics depending on noise analysis in the rail–wheel contact.

Proposed adhesion control system

For our proposed system, we can use control algorithms described in [23]. As one of the main ones distinct from the existing patent, the system can adjust the adhesion of railway vehicles in real-time mode by means of the correction data about adhesion coefficient.
In our case, we propose, for the determination of an adhesion coefficient, to use an acoustic diagnostic method of the contact zone. For obtaining a noise spectrum, it is necessary to mount directional microphones in vertical and horizontal planes for scanning of noises.

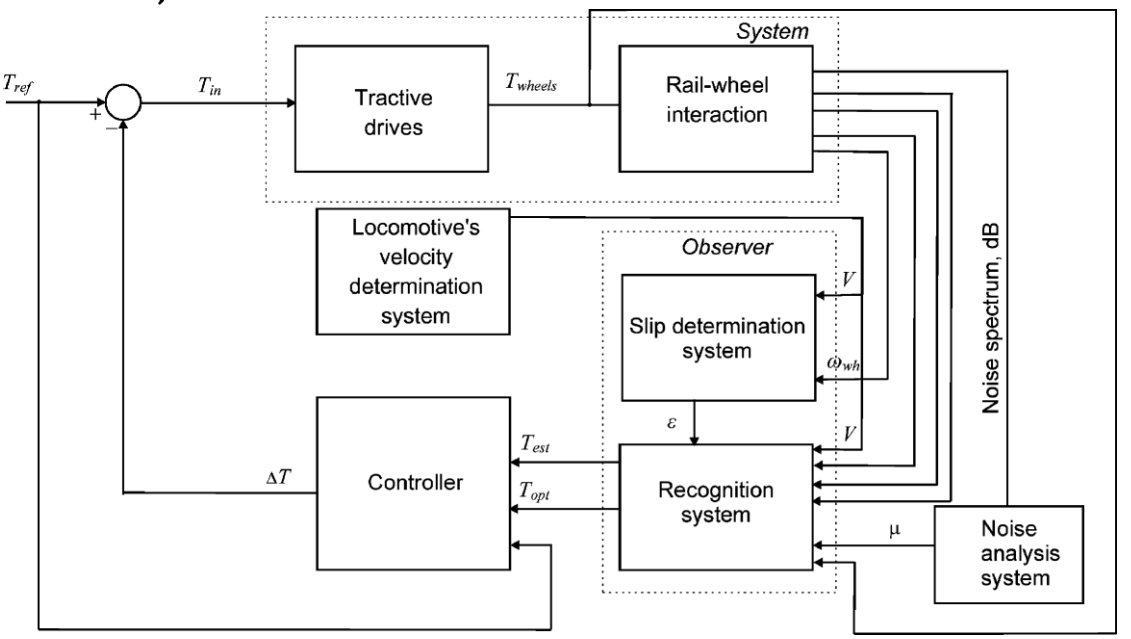


Fig. 2. Block diagram of the adhesion control system.

The proposed control system is presented in Fig. 2. The variables and parameters are presented in Fig. 2: T_{ref}—reference torque given by driver; T_{in}—input motor torque; T_{opt}—optimal motor torque; T_{est}—estimated adhesion torque; T_{wheels}—tractive torque applied to wheel set; DT—feedback torque signal; and m—maximum adhesion coefficient detected by noise analysis system.

The detection of the adhesion coefficient is based upon noise spectrum analysis in the wheel–rail contact and using GPRS and GPS technologies. GPS satellite system is used for obtaining a position of a railway vehicle at a specific moment of time. After receiving the current position on the curve, the track characteristics for the current position can be obtained by means of the GPRS from the station computer. The obtained noises are processed by a special algorithm to obtain noise characteristics for certain frequency bands. By looking up a special database data, received from experimental and theoretical research, the dependence of the adhesion coefficient on noise and track characteristics, vehicle velocity, relative slip, the lateral displacement and the angle of attack can be obtained.

To describe the torque dynamics of the convector and the traction drive, it is necessary to use a low-pass filter

$$T_{in} = \frac{1}{ts + 1} T_{ref}, \quad (3)$$

where t is a time constant.

In the tractive mode, the optimum of adhesive torque between the wheel of a railway vehicle and rail can be calculated for a wheel set by observer from Eq. (1):

$$T_{opt} = \frac{1}{i} (F_{al} + F_{ar}) r, \quad (4)$$

where F_{al} and F_{ar} are adhesive forces for left and right wheels of a wheel set, i is a conversion ratio of the tractive gearbox.

According to [24], the optimal adhesion forces F_{al} and F_{ar} should be situated in stable zone, which are shown in Fig. 3. As we can see, the optimal adhesive forces can be calculated when the relative slip is close to 3%.

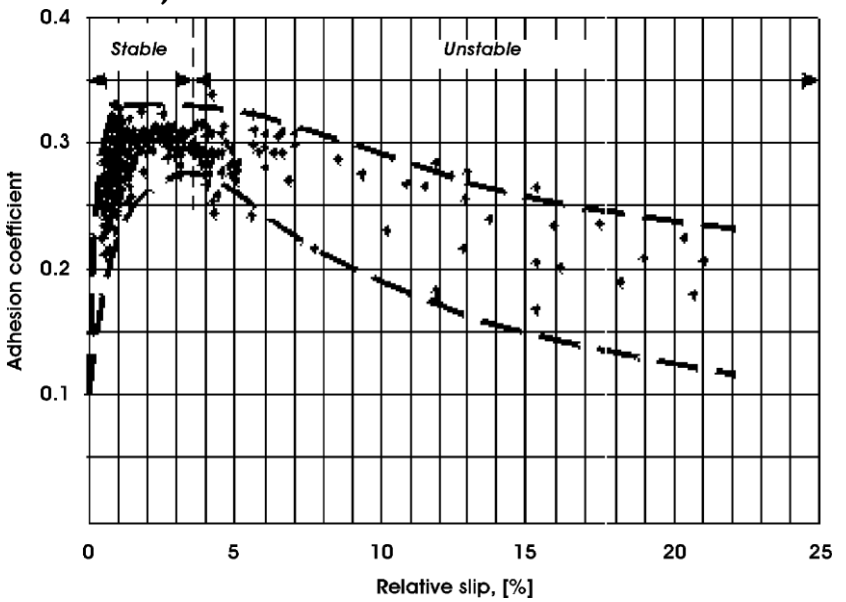


Fig. 3. Measured values of adhesion coefficient [14].

To model tractive torques applied to wheel sets, we use

$T_{\text{wheels}} = Tini.$ (5)

For estimation of adhesion torque and adhesion coefficient we use a method similar to those described in [7,25,26]. This method allows us to see how to change the adhesion coefficient and adhesion torque dependent on our proposed control strategy.

The relationship between wheel velocity and the tractive torque is

$$T_{\text{est}} = T_{\text{wheels}} - J_{wheels} \frac{V}{r}, \quad (6)$$

where J is an inertia of wheel set. To use Laplace transformation and adapt primary order low-pass filter, the following equation is obtained:

$$T_{\text{est}} = T_{\text{wheels}} - J_{wheels} \frac{1}{r} \frac{1}{t_0 s + 1} V(s), \quad (7)$$

where t_0 is a time constant of the observer. The adhesion coefficient can be estimated by using the following equation:

$$m_{\text{est}} = \frac{T_{\text{est}}}{Nr}, \quad (8)$$

where N is weight load from a wheel set to a railway track.
The adhesion feedback controller uses fuzzy logic. The proposed system allows limiting the optimum torque according to the reference torque given by a driver of railway vehicle. The feedback path of the system is DT, and the change of this variable can be calculated as

$$DT = T_{ref} — T_{opt} + k, \quad (9)$$

where k is a coefficient that is dependent on two parameters, described in Table 1 and received by means of fuzzy rules.
The set of fuzzy rules also is presented in Table 1. Here, N and P stand for negative and positive values and S, M, and B means small, medium and large values. ZE means zero and SM represents a state between small and medium values. The control surface of these rules is shown in Fig. 4.
The control goal of this strategy is to reach the optimal adhesion coefficient.

Table 1
The set of rules for the controller

$T_{ref} — T_{opt}$	T_{opt}	
	ZE	*P*
N	*ZE*	*PS*
ZE	*ZE*	*PSM*
PS	*ZE*	*PSM*
PM	*ZE*	*PM*
PB	*ZE*	*PB*

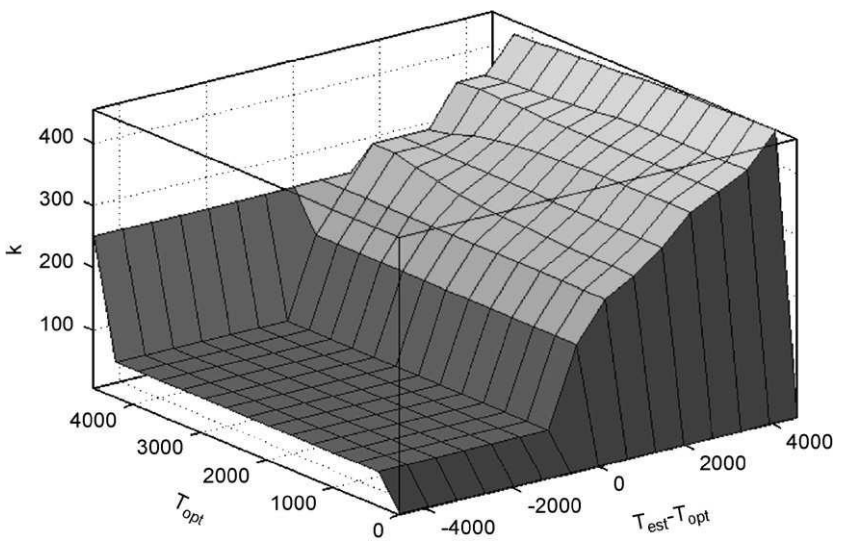


Fig. 4. Control decision of fuzzy rules.

Design and simulation model

The evolution of the proposed system was performed by means of a simulation on a railway vehicle DEL-01.

This diesel train is produced by Holding Company ‘‘Luganskteplovoz’’ in Ukraine.
For the generation of the simulation model the non-linear MBS software package called Simpack has been used. According to the construction design and characteristics described in [17], the main coach of the railway vehicle has only one tractive bogie with two tractive drives. Each of these drives is equipped with an AC motor. The proposed control strategy was modelled in Matlab/Simulink. The Simpack model of the bogie was linked with the control unit in Matlab/Simulink by means of the SIMAT-interface. Based on the software packages described above the system was investigated by using co- simulation.
In the observer for Eq. (1) we used the coefficients listed in Table 2. These coefficients were obtained for the wheel and rail profiles shown in Figs. 5 and 6. The wheel and rail profiles were chosen from the list of profiles recommended by HC ‘‘Luganskteplovoz’’ for research purposes. The variables are presented in Table 2: m—adhesion coefficient between a wheel and rail; N—weight load from a wheel to a rail, kN; v—vehicle velocity, m/s; and y—cross-motion of the wheel pair on track, mm.
As an example of computed results, a simulation of the movement of the bogie in tractive mode is presented. The track is a short straight and Fig. 7 presents the dependence between the maximum adhesion coefficient and distance along the track. This allows simulating different adhesion conditions between wheels and rails.
Table 2
Coefficients of relation (1)

A_1	0
A_2	—0.193
A_3	0.0379415
A_4	3.31448
A_5	2.115
T_1	0.026+2.38m
T_2	m/0.406
T_3	$12.4/(0.2389371–1.6353N+4.76N^2)$
T_4	$0.429348–0.0000696802N$
T_5	$12.25/\exp(—0.523\ln(v)+3.725)$
T_6	$12.25/(0.0000050377/\exp(y)+0.000352571y^2+0.083)$
T_7	$1/(0.00000747/\exp(y)\times 0.00063638y+2.37)$
T_8	1

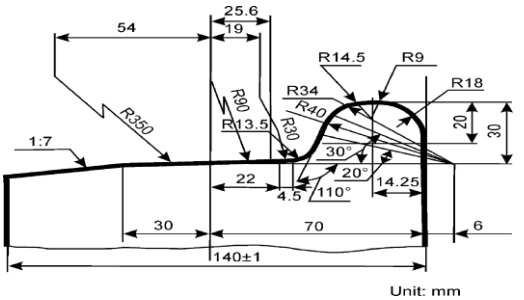
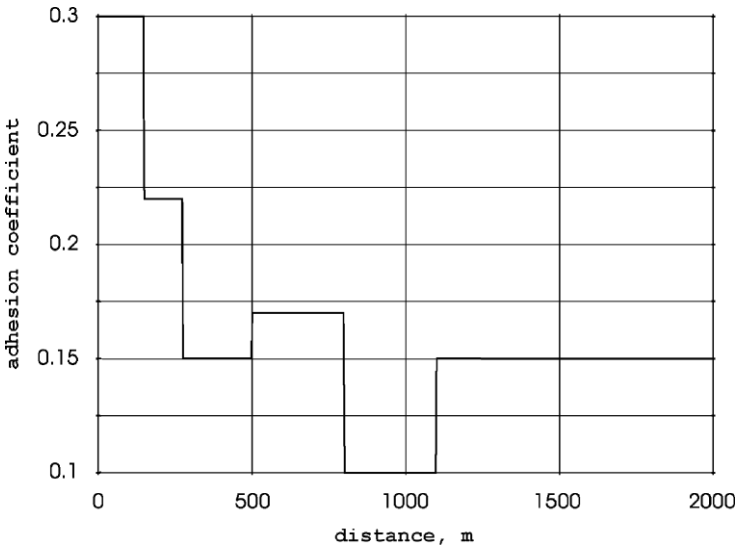


Fig. 5. Rail profile [27].
For this simulation, the values for adhesion coefficient m depending on noise in Table 2 for the contact zone, which allows adjusting values for coefficients T_1 and T_2, was taken from the Simpack model.
These values are equivalent to values of the adhesion coefficient m_{max} depending on the position of a railway vehicle on the track.
Fig. 8 shows the calculated values of torques, adhesion coefficients, distance and vehicle velocity as a function of the time.
The obtained results confirm the satisfactory work of the proposed system.

Conclusions and further research

The proposed control system allows using optimal tractive efforts by means of control of torque motors, which depends on adhesion characteristics at the moment of vehicle movement. These characteristics can be received by means of the detection of adhesion coefficient depending on noise in rail–wheel contact. This method reduces wearing of contact bodies and tractive units. Therefore, it is necessary to do further research

Fig. 6. Wheel profile [27].



in the field of stability, robustness and convergence for the proposed system. Also, for the correct work of the system in real conditions more detailed study and experimental research need to be performed on the dependence of the adhesion coefficient from noise in rail–wheel contact for different friction conditions. After that, it is possible to create a mathematical model of noise prediction by means of taking into account tribological characteristics of bodies' interaction.

The future plan is to confirm this simulation of the complex mechatronic system of a railway vehicle by experiments using real vehicles on service lines.

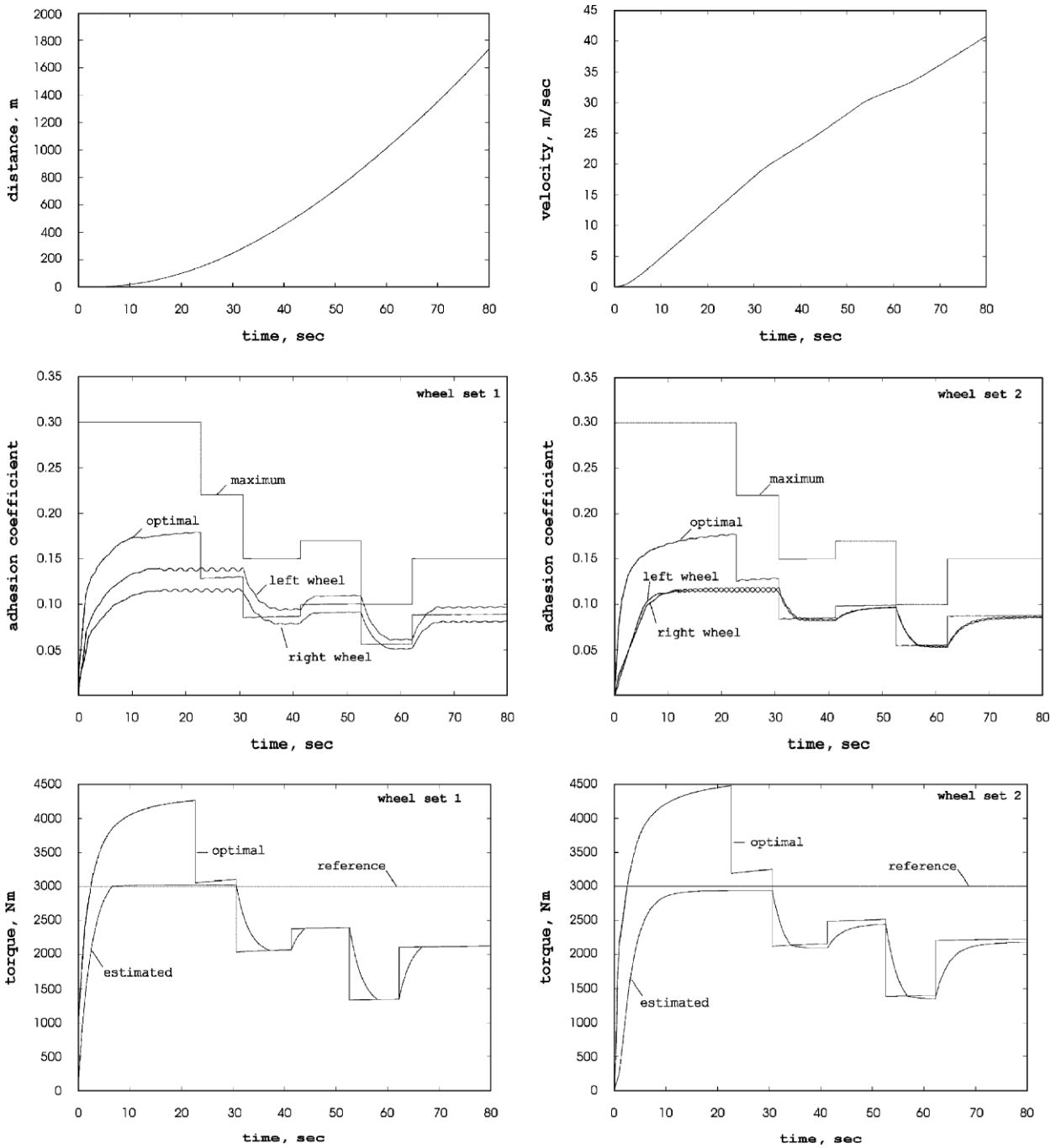


Fig. 8. The results obtained for a railway vehicle under different adhesion conditions from Simpack and MATLAB/Simulink co-simulation.

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