Revisiting the adjustable mode of a locomotive startup to ensure the best use of the clutch

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Abstract. It is known that a locomotive startup process usually consists of two consecutive phases (initial and final). From the point of view of the adhesive force implementation, it is important how the driving force changes during each of the startup phases and what the length of each phase is. The law of distribution of the realized values of the adhesion coefficient and the use of adhesive force depend on the law of change in the startup driving force we use to approach the limit of adhesion. The choice of the startup mode can be crucial in the most heavy-duty mode of the locomotive – when starting-up and setting the train in operation. As a result of the conducted research, it was established that immediately after the motion onset, acceleration should not exceed 0.5% of the maximum possible for these conditions. It means that in the first sampling interval (up to approximately 5% of the starting duration), the driving effort must be sufficiently small, namely, \( F = 0.005F_{\text{max}} \). Then, it must slowly increase to about 15–20% of the starting duration over each sampling interval. It is established that in the startup mode with the proposed step-by-step method of controlling the driving force, the speed of the locomotive almost completely coincides with its corresponding speed during continuous adjustment. Deviation makes up not more than 2-3%. It can be explained by the inertia of the wheelset drive of the locomotive, which will not lead to clutch stalling and wheel slipping.

1. Introduction
The interaction of a wheel and a rail is the physical basis for the rolling stock movement on railways. Traffic safety and the main technical and economic indicators of the tracks and rolling stock largely depend on the parameters of this interaction.

For the development of automatic startup systems that ensure normal conditions for the implementation of the locomotive’s adhesive force, an important role plays the correct choice of the law of the driving force change during the starting duration of a locomotive, as well as the value of the adopted maximum driving force and the nature of its change during the movement of a train.

It is known that a startup process usually consists of two consecutive phases. At first it is carried out with a gradual increase in the driving force and acceleration, and then it is accompanied by a slow increase or, if possible, constant acceleration. The ratio between the duration of these phases depends on the adopted startup system and in some types of locomotives the driving force reaches its full value only in the middle of the starting period or even towards the end of it. In the context of the adhesive force implementation, it is important how the driving force changes during each of the startup phases and what the length of each phase is. The law of distribution of the realized values of the adhesion coefficient and the use of adhesive force depend on the law of change in the startup driving force we use to approach the limit of adhesion [1,2,3,4].
The choice of the startup mode can be crucial in the most heavy-duty mode of the locomotive – when starting-up and setting the train in operation. In the practice of rolling stock operation, quartz sand is used to increase the adhesion coefficient. However, the use of sand leads to clogging of the tracks and increases the likelihood of wear and tear of the moving parts of the locomotive undercarriage. After passing of the locomotive, the sand remaining on the rails creates additional resistance to the train movement, reaching 12%, and the sand trapped on the rubbing parts of the track and rolling stock contributes to their more abrasive wear [5,6].

The papers [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18] are dedicated to the matter of dependence of the coefficient of adhesion of locomotive wheelsets with rails in different operating modes. Therefore, the matter of ensuring the highest values of adhesion coefficients after the completion of the locomotive startup process and reducing sand consumption is relevant.

2. Object and methods of research
In research works [1, 2, 5, 19] the theoretically justified law of change of the driving force \( F \) (minus movement resistance) in the locomotive startup mode as a function of time is given, which ensures the shortest acceleration time without slipping of the locomotive wheelsets. The corresponding dependence of the velocity \( V \) on the time in such a startup mode was also obtained. It is proposed to present the given dependencies in relative terms: the traction force minus the resistance to movement is attributed to the limiting value of the traction force according to the conditions of adhesion at the end of the startup \( (F_{\text{max}}) \), the speed - to the working speed \( (V_{\text{max}}) \) of the rolling stock’s movement (at the end of startup), and time – to the duration of the startup mode \( (t_{DS}) \). At the same time, the starting duration does not include the time from the moment of switching on the starting device (the beginning of movement of the control element) to the beginning of stable operation of the engine on fuel [20]. In the most general form, it will provide the quantitative results of the startup process analysis of any railway locomotive. In Fig. 1, graphs of these dependencies are shown with solid lines.

![Figure 1](image-url)

**Figure 1.** Change of traction effort and locomotive speed: with smooth control of the traction effort (solid line \( F/F_{\text{max}} \)) and speed (solid line \( V/V_{\text{max}} \)) from the starting duration; with two-stage regulation of the traction effort (dashed lines 4) with close to continuous speed regulation (dashed lines of speed 2 and 3); with two-stage regulation of the traction effort (dash-dotted line 5) and speed (dash-dotted line 6), with acceleration limited at the second stage

With continuous control of the speed and tractive effort of the driving wheelsets of the locomotive, in order to ensure startup with the best adhesion (without skidding), it is necessary to change the speed
\(v = V / V_{\text{max}}\) as a function of time \((\tau = t / t_{\text{DS}})\) with the help of continuously varying traction effort \((f = F / F_{\text{max}})\). In order to ensure the best adhesion of the wheel and the rail, the traction effort should be changed so as to be at the lower border or below the shaded area shown in Fig. 1. With stage-by-stage regulation of the driving force, at each stage in a limited time interval the driving force is unchanged and should not exceed the boundaries of the shaded area. The number of stages and their time intervals may be different. It is necessary to choose the smallest number of stages and determine the time intervals of the stages so that the starting duration slightly (no more than 3-4\%), which corresponds to GOST R 55231-2012 on the error of the rotation speed setting \([21]\) exceeds the starting duration with continuous control.

From Fig. 1, it can be seen that, in the given scale, the speed graph is almost linear throughout the entire starting duration interval, except for the area near \(t = 0.23 \cdot t_{\text{DS}}\) (in the vicinity of the inflection point of the traction effort curve). Two linear sections of the speed (in Fig. 1, dotted segments 1 and 2 with a common point when \(t = 0.23 \cdot t_{\text{DS}}\)) correspond to two constant values of the traction effort (dotted lines 3 and 4). The value of traction effort at each time interval can be obtained by assuming the passage of the first segment through the origin of coordinates and the point \(t = 0.2 \cdot t_{\text{DS}}:\)

\[
F_0 = f(0.2) \cdot F_{\text{max}},
\]

where \(f(0.2) = 5 \cdot 10^{-5} \cdot \left( e^{100 \cdot \tau^2} - 1 \right) + 0.125 \cdot \tau^2 \left| \tau = 0.2 \right. = 0.00768 \) \([1]\).

Assuming that the second segment passes through the points \(t = 0.3 \cdot t_{\text{DS}}\) and \(t = t_{\text{DS}}\) of the speed curve, we obtain the value of the traction effort:

\[
F_1 = \frac{f(1) - f(0.3)}{1 - 0.3} \cdot F_{\text{max}} = 0.977 \cdot F_{\text{max}}.
\]

In this case, the speed \((v = V / V_{\text{max}})\) will vary in direct proportion to the time \((\tau = t / t_{\text{DS}})\) for the first segment 1 (at the initial moments of startup)

\[
v_0(\tau) = \frac{F_0}{F_{\text{max}}} \cdot \tau,
\]

and for the second segment in linear fashion

\[
v_1(\tau) = \frac{F_1}{F_{\text{max}}} \cdot \tau + \left[ f(1) - \frac{F_1}{F_{\text{max}}} \right].
\]

These two functions have a common point \(\tau_{12}\), at which \(v_0(\tau_{12}) = v_1(\tau_{12})\):

\[
\tau_{12} = \frac{f(1) - F_1}{F_1 - F_0} \cdot \frac{F_{\text{max}}}{F_{\text{max}}} = 0.23.
\]

This implies that with a good approximation, the functions of speed from time in two time sections obtained in \([1]\) can be represented as:

\[
v(\tau) = 5 \cdot 10^{-5} \cdot \left( e^{100 \cdot \tau^2} - 1 \right) + 0.125 \cdot \tau^2 \approx 0.00768 \cdot \tau \quad \text{at} \quad 0 \leq \tau \leq 0.23
\]

\[
v(\tau) = 0.94 \cdot \tau + 0.01375 \cdot e^{-52(\tau-0.23)} + 0.03 \cdot \tau^2 - 0.215 \approx 0.977 \cdot \tau - 0.28 \quad \text{at} \quad 0.23 \leq \tau \leq 1
\]

Such a change in speed is ensured by constant traction efforts \((1)\) and \((2)\). From Fig. 1 it can be seen that in the interval from \(t = 0.23 \cdot t_{\text{DS}}\) to about \(t = 0.5 \cdot t_{\text{DS}}\) the traction effort \((\text{line 4})\) is higher than the permissible limit that provides the best adhesion. \(t = 0.23 \cdot t_{\text{DS}}\) to about \(t = 0.5 \cdot t_{\text{DS}}\), the pulling force \((\text{line 4})\) is higher than the permissible limit that provides the best adhesion. For the traction effort not to exceed the permissible limit, it is necessary to reduce it in the second section, which will certainly lead to an increase in the starting duration \(t_{\text{DS}}\).
3. Research results and their discussion

The analysis showed that the choice of intervals for stage-by-stage control of the traction effort greatly influences the duration of the startup mode. Therefore, with two-stage regulation, the starting duration increases by at least 11.9%. The smallest increase in the starting duration corresponds to the intervals from \( t = 0 \) till \( t = 0.31 \cdot t_{DS} \) and from \( t = 0.31 \cdot t_{DS} \) till \( t = t_{DS} \).

In Fig. 1 the dash-dotted polygonal curve 5 (the break point \( t = 0.31 \cdot t_{DS} \)) of the traction effort and the corresponding dash-dotted polygonal curve 6 of the speed comply with such regulation. If we choose another break point at \( t \neq 0.31 \cdot t_{DS} \), then the starting duration will be more than 11.9% compared with continuous adjustment of the traction effort.

To reduce the starting duration, the number of regulation stages must be increased. So with a three-stage regulation of the traction effort, the starting duration increases by at least 6.2% (the best intervals: 1) from \( t = 0 \) till \( t = 0.28 \cdot t_{DS} \); 2) from \( t = 0.28 \cdot t_{DS} \) till \( t = 0.38 \cdot t_{DS} \); 3) from \( t = 0.38 \cdot t_{DS} \) till \( t = t_{DS} \)). In Fig. 2, the stepped line 1 corresponds to the three stages of the traction effort, and line 2 corresponds to the three stages of speed.

![Figure 2](image)

**Figure 2.** Dependencies of traction effort (lines 1 and 3) and speed (lines 2 and 4) on the starting duration, respectively, with three and four-stage regulation

With a four-stage regulation, you can select intervals as follows: \( 0 - 0.23 \cdot t_{DS} \); \( 0.23 \cdot t_{DS} - 0.27 \cdot t_{DS} \); \( 0.27 \cdot t_{DS} - 0.38 \cdot t_{DS} \) and \( 0.38 \cdot t_{DS} - 1.0 \cdot t_{DS} \), so that the starting duration increased by only 4.5%. In Figure 2, lines 3 and 4 correspond to the stages of traction effort and speed.

It was established that with four or more stages of regulation of the traction effort, the startup mode with the best adhesion (without slipping) and the shortest duration is possible.

The driving force of a locomotive is determined by the locomotive’s diesel power or the power of locomotive’s wheelsets of the driving engines. The driving force \((F/F_{\text{max}})\) must change so that the speed of the rolling stock at any time was as close as possible to the curve \((v/v_{\text{max}})\) in Fig. 1. With stage regulation of power (for example, eight-stage regulation, as in TEM-7 diesel locomotive [22]), it is necessary to determine discrete time intervals and power levels (tractive effort) at each discrete interval so that the speed becomes close to \((v/v_{\text{max}})\).

To reduce the starting duration, the number of regulation stages must be increased. So with a three-stage regulation of the traction effort, the starting duration increases by at least 6.2% (the best
intervals: 1) from $t = 0$ till $t = 0.28 t_{DS}$; 2) from $t = 0.28 t_{DS}$ till $t = 0.38 t_{DS}$; 3) from $t = 0.38 t_{DS}$ till $t = t_{DS}$). In Fig. 2, the stepped line 1 corresponds to the three stages of the traction effort, and line 2 corresponds to the three stages of speed. With a four-stage regulation, you can select intervals as follows: $(0 - 0.23 t_{DS}; 0.23 t_{DS} - 0.27 t_{DS}; 0.27 t_{DS} - 0.38 t_{DS}$ and $0.38 t_{DS} - 1.0 t_{DS}$), so that the starting duration increased by only 4.5%. In Figure 2, lines 3 and 4 correspond to the stages of traction effort and speed. Thus, with four or more regulation stages of the traction effort, the startup mode with the best adhesion (without slipping) and with the shortest acceleration time is possible.

The analysis showed that immediately after the motion onset, acceleration should be sufficiently small so that there isn’t any slipping, for example, acceleration should not be greater than 0.5% of the maximum corresponding to $F_{\text{max}}$. This means that in the first sampling interval (up to approximately 5% of the starting duration), the traction effort must be sufficiently small, namely, $F = 0.005 F_{\text{max}}$. Such traction effort should provide a minimum stable motor speed [21]. Then, to about 15–20% of the starting duration, it should slowly increase over each sampling interval. Only when the speed exceeds 5% of the nominal (maximum) acceleration can take values of more than 20% of the maximum at the remaining sampling intervals, which can be extended, compared to short initial ones. Table 1 presents quantitative characteristics of the traction effort staging in the startup mode of the rolling stock without slipping to ensure the shortest starting duration.

Figure 3 presents a graphic illustration of the proposed traction effort staging at the initial discrete intervals in accordance with the data in Table 1. Here, curve 1 is the theoretically justified in [19] dependence of relative traction effort on relative time, and the stepped dashed line 3 is its step approximation. Curve 2 corresponds to the theoretically justified relative speed; dashed line 4, almost coinciding with line 2, is the relative velocity corresponding to the stage-by-stage dependence of acceleration.

![Figure 3](image_url)

**Figure 3.** Graphic illustration of stage-by-stage regulation of traction effort at five initial intervals: curve 1 – the dependence of relative traction effort on relative time theoretically grounded in [19], dashed line 3 – its step approximation. Curve 2 corresponds to the theoretically justified relative speed; dashed line 4 is the relative speed corresponding to the stage-by-stage dependence of acceleration.
Table 1. Traction effort of the startup mode at discrete time intervals

| Startup mode interval $\Delta t_k$ | Interval start time $t_{\text{нач}}$ | Interval end time $t_{\text{кон}}$ | Interval traction effort $F_K$ |
|-----------------------------------|--------------------------------------|----------------------------------|-------------------------------|
| $\Delta t_1$                      | 0,00\,$t_{DS}$                       | 0,05\,$t_{DS}$                   | $F_1 = 0,0045\,F_{\text{max}}$|
| $\Delta t_2$                      | 0,05\,$t_{DS}$                       | 0,10\,$t_{DS}$                   | $F_2 = 0,014\,F_{\text{max}}$  |
| $\Delta t_3$                      | 0,10\,$t_{DS}$                       | 0,15\,$t_{DS}$                   | $F_3 = 0,028\,F_{\text{max}}$  |
| $\Delta t_4$                      | 0,15\,$t_{DS}$                       | 0,19\,$t_{DS}$                   | $F_4 = 0,051\,F_{\text{max}}$  |
| $\Delta t_5$                      | 0,19\,$t_{DS}$                       | 0,235\,$t_{DS}$                  | $F_5 = 0,120\,F_{\text{max}}$  |
| $\Delta t_6$                      | 0,235\,$t_{DS}$                      | 0,28\,$t_{DS}$                   | $F_6 = 0,670\,F_{\text{max}}$  |
| $\Delta t_7$                      | 0,28\,$t_{DS}$                       | 0,35\,$t_{DS}$                   | $F_7 = 0,910\,F_{\text{max}}$  |
| $\Delta t_8$                      | 0,35\,$t_{DS}$                       | 1,00\,$t_{DS}$                   | $F_8 = 0,975\,F_{\text{max}}$  |

Figure 4 shows graphs of the stage-by-stage regulation of the traction effort in the startup mode in accordance with the data in Table 1 at all time intervals.

Figure 4. Graphs of relative dependencies of traction effort and speed on the starting duration with eight-stage regulation: curve 1 is a theoretically justified in [19] dependence of relative traction effort on relative time, dashed line 3 is its eight-step approximation; curve 2 corresponds to the theoretically justified relative speed, and dashed line 4 is the relative speed corresponding to the stage-by-stage dependence of the acceleration.
It can be shown that in the startup mode, with the proposed stage-by-stage method of traction effort regulation, the speed will almost completely (the error does not exceed 2%) coincide with the same speed under continuous regulation. It is important to note that due to the inertia of the locomotive wheelsets’ drive when using stage-by-stage regulation of the traction effort, slight deviations of the step function (curve 3) from curve 1 at speeds of over 20% of the working speed do not lead to clutch stalling and wheel slipping.

Conclusions
1. Analysis of the starting duration showed that its duration depends on the choice of the interval number in the stage-by-stage regulation of the traction effort. It was established that in four or more stages of traction effort regulation, it is possible to obtain a startup mode with the best adhesion (without slipping) and with the shortest acceleration time.
2. As a result of the research, it was established that immediately after the motion onset, the acceleration should not exceed 0.5% of the maximum possible for these conditions. It means that in the first sampling interval (up to approximately 5% of the starting duration), the traction effort must be sufficiently small, namely, $F = 0.005 F_{\text{max}}$. Then, up to about 15–20% of the starting duration, it should slowly increase over each of the five sampling intervals. Only when the speed exceeds 5% of the nominal (maximum) acceleration can take values of more than 25% of the maximum at the remaining three sampling intervals, which can be more extended, compared to the short initial ones.
3. It was established that in the startup mode, with the proposed eight-stage method of traction force regulation, the speed of the locomotive will almost completely coincide with its corresponding speed under continuous regulation. The deviation is not higher than 2%.

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