Calculation of the Traction Effort of Switching Locomotive

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Abstract- This paper presents the method of calculation of traction effort of switching locomotive. The calculations are based on Czech-origin switching locomotive ChME3, that type of locomotive has been chosen, because almost one third of switching locomotives used in Estonia is ChME3 [1]. For the accomplishment and visualization of calculations the MathCAD software package has been used.

I. INTRODUCTION

Railroads, invented at the beginning of 19th century, still provide the basis for the most efficient means of moving goods and passengers around the world [2]. There are three main types of locomotives: – passenger locomotives, freight locomotives and switching locomotives. The last one is optimized for switching operations and used mainly at rail stations to compound and demount the trains [2]. On account of their application, it’s quite difficult to receive a high efficiency factor, so the theoretical calculations should help choose the right working mode of locomotive drives.

The velocity of a locomotive depends on two forces – the traction effort of locomotive and the motion resistance force [3]. Traction effort of locomotive is produced by the locomotives traction motors. The motion resistance force represents a sum of forces influencing the train, while it is moving, and the peculiarities of the rail road, like sloping, curve radius, friction, etc. The traction effort is the train pushing force provided by the traction motors of a locomotive. The locomotive accelerates if the traction effort is larger than the motion resistance force; deaccelerates if the traction effort is smaller and moves at a constant velocity or stands if they are equal. It means that the velocity of a locomotive depends on the difference between these two forces.

There are two different ways to find the traction effort of a locomotive: first is theoretical, where the traction effort is calculated basing on technical data and mechanical properties; second is empirical, based on tests and measurements. The paper presents the theoretical one.

II. THE MOTION RESISTANCE FORCE

The force opposite to locomotives motion could be divided into two parts: the stretch resistance forces and the train resistance forces [5].

The stretch resistance force is a sum of forces related to the rail-road properties: road sloping, road curve radius. The slope shows tendency of increasing or decreasing of road’s level, one per mil is used for slopes estimation (‰). The rail-road slope of 1‰ means that the road rises 1m high per 1000 m of a distance. With a slope of 10% the locomotive can pull only a half (or even less) of its rated load, it would be shown later on. This means that the slope is a very valuable characteristic in the traction force calculation. During the curving of a locomotive, the extra friction forces between wheels and rail-track are arising. If these forces were very high, they could damage the rail-track or locomotive’s traction system, so the curving radius should be taken into account.

Also the resistance forces of a locomotive itself produce on the traction effort. They are rolling resistance force, bearing resistance, gearbox resistance, starting resistance, dynamic resistance and air resistance. A wheel on the rail-track generates a longitudinal force called rolling resistance. The force is opposite to the direction of motion and is proportional to the normal force on the wheel [6]. The bearing resistance and the gearbox resistance are mechanical forces that could be taken into account as a mechanical gain factor. The dynamic resistance takes into account the mass of locomotive and the wagons. A locomotives frontal area and an air density could be merged as one air resistance force. Moreover, the efficiency factor of all drives should be taken into account.

III. INITIAL DATA

A diesel-electric shunting locomotive ChME3 is taken as an example for the calculations. ChME3 has a diesel engine, which produces a torque for DC generator. DC generator feeds 6 traction motors that produce the traction effort to push the locomotive. In more details the traction system of ChME3 was described in the previous researches [2]. The technical data of a locomotive is presented in Table I.

The additional coefficients needed for the calculations could be found in the handbooks, for ChME3 they are [4], [7]. Locomotive’s air resistance force (C\text{air}) depends on the type of locomotive’s body, for the 02-BT the value of locomotives air resistance force C\text{air}=1.1. Moreover, the air resistance coefficient for wagons behind the locomotive is C\text{wag}=0.11 (for the 02-BT). e air density coefficient ρ\text{air}=1.225 kg/m³. The inertial coefficient that takes into account the largest rolling part σ=1.06. The rail rolling resistance coefficient μ\text{loc}=2.10^{-3}. Usually the switching locomotives operate with high load, which means that the main variable that should be taken into account is the weight of the wagons. In that case the average load on one axle of wagon (m\text{axle}) is very important. As an example, load on one axle of wagon is m\text{axle}=21 tonne. In case, the wagon has 4 axles, the mass of wagon (m\text{wag}) is calculated by (1) and equal to 84tonne.
The aerodynamic force that depends on the velocity of locomotive and the number of wagons, could be calculated by (5), where $v$ is the velocity of locomotive and $A_{fl}$ is a frontal area of locomotive (Table I).

$$F_{\text{air}} = \frac{1}{2} \cdot \rho_{\text{air}} \cdot C_{\text{loc}} \cdot n \cdot C_{\text{wag}} \cdot A_{\text{fl}} \cdot v^2 \quad (5)$$

The sum of forces (3), (4) and (5) is the force (6) that is opposite to locomotive’s traction force.

$$F_{\text{load}} = F_{\text{fr}} + F_{\text{road}} + F_{\text{air}} \quad (6)$$

The maximum transmittable traction effort of the locomotive according to Curtius-Kniffler (7) and (8), where $\mu_{\text{dry}}$ is an adhesive coefficient for a dry surface and $\mu_{\text{wet}}$ is an adhesive coefficient for a wet surface [8]; $v$ is a velocity of a locomotive in km/h.

$$\mu_{\text{dry}} = \frac{7.5}{v + 44} + 0.161 \quad (7)$$

$$\mu_{\text{wet}} = \frac{7.5}{v + 44} + 0.13 \quad (8)$$

The maximum traction effort could be calculated by (9) and (10) with respect to changing of the frictions forces with different atmosphere conditions (dry and wet surfaces).

$$F_{\text{max,dry}} = \mu_{\text{dry}} \cdot m_{\text{loc}} \cdot g \quad (9)$$

$$F_{\text{max,wet}} = \mu_{\text{wet}} \cdot m_{\text{loc}} \cdot g \quad (10)$$

With the atmospheric condensation the wheel-to-rail-road friction shrinks, that’s why the wet surface adhesive coefficient ($\mu_{\text{wet}}$) is over than the dry surface adhesive coefficient ($\mu_{\text{dry}}$). That’s why the traction effort in case of wet surface (10) should be taken as the maximum traction effort of a locomotive.

The maximal traction effort of a locomotive (10) should be greater than the sum of the opposite forces (6), otherwise the load forces will brake the locomotive. The inequality (11) presents that mathematically.

$$F_{\text{max,wet}} > F_{\text{load}} \quad (11)$$

The calculations of the traction effort for a different road slope are presented in Fig. 1 - Fig. 3 ($\pi$ -axle). There are three-dimension diagrams, because there are three main parameters that could be frequently changed during the movement of a locomotive. They are road slope, number of wagons (Fig. 1 - Fig. 3 x-axle) and velocity (Fig. 1 - Fig. 3 y-axle), if some of them are constant, the diagram becomes two dimensional. The upper surface on the figures is the traction effort produced by traction motors, and the lower surface on the figures is the force that is opposite to the movement (load surface).

From Fig. 1, it could be seen that with a road slope of 0% the surface that describes the traction effort of locomotives traction motors is almost always below the load surface, only area that is above is the start-up area with load more than 45 wagons. In mentioned area it would be overload and the locomotive could not start-up. In other cases in the presented bounds there are no overloads and the locomotive can operate in that area (working area of locomotive).

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**TABLE I**

**THE TECHNICAL DATA OF CHME3 [1], [4], [7]**

<table>
<thead>
<tr>
<th>Year of manufacture</th>
<th>1980-87</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel arrangement</td>
<td>C-C</td>
</tr>
<tr>
<td>Diesel engine power, kW</td>
<td>993</td>
</tr>
<tr>
<td>Power converter type</td>
<td>DC/DC</td>
</tr>
<tr>
<td>Traction generator power, kW</td>
<td>885</td>
</tr>
<tr>
<td>Traction motor power, kW</td>
<td>123</td>
</tr>
<tr>
<td>Number of traction motors</td>
<td>6</td>
</tr>
<tr>
<td>Maximal traction effort, kW (HP)</td>
<td>736 (1000)</td>
</tr>
<tr>
<td>Auxiliary devices power, kW</td>
<td>45</td>
</tr>
<tr>
<td>Velocity limit, km/h</td>
<td>95</td>
</tr>
<tr>
<td>Minimum road curve radius, m</td>
<td>80</td>
</tr>
<tr>
<td>Size type</td>
<td>02-BT</td>
</tr>
<tr>
<td>Frontal area, m²</td>
<td>12.3</td>
</tr>
<tr>
<td>Length, m</td>
<td>17.2</td>
</tr>
<tr>
<td>Working mass*, tonnes</td>
<td>123±3%</td>
</tr>
<tr>
<td>Traction clutch, kN</td>
<td>226</td>
</tr>
<tr>
<td>Petrol reserv, l</td>
<td>6000</td>
</tr>
<tr>
<td>Total efficiency factor, %</td>
<td>27.5</td>
</tr>
</tbody>
</table>

*Working mass with 67% of petrol and sand resources.

Where $m_{\text{wag}}$ is the total working mass of the locomotive (Table I), $n$ is the number of wagons in the train and $g$ is the local gravitational field that is equivalent to the free-fall acceleration 9.807 m/s².

$$m_{\text{wag}} = m_{\text{axle}} \quad (1)$$

The total efficiency factor in Table I also includes the efficiency factor of a diesel engine that is very low for all internal combustion engine (ICE). For the traction effort calculation such a detail as energy flow analyze is not needed. It is enough if mechanical efficiency factor ($\eta_{\text{mech}}$=98 %), traction generator efficiency factor ($\eta_{\text{gen}}$=94 %) and traction motor efficiency factor ($\eta_{\text{mot}}$=90 %) are taken into account. In that case the total efficiency factor ($\eta_{\text{tot}}$) is calculated by (2) and equal to 82.9 %.

$$\eta_{\text{tot}} = \eta_{\text{mech}} \cdot \eta_{\text{gen}} \cdot \eta_{\text{mot}} \quad (2)$$

IV. **THE TRACTION EFFORT CALCULATION**

The static friction force could be calculated by (3), where $m_{\text{loc}}$ is the working mass of the locomotive (Table I), $n$ is the number of wagons in the train and $g$ is the local gravitational field that is equivalent to the free-fall acceleration 9.807 m/s².

$$F_p = 7.5 \cdot 10^{-3} \cdot (m_{\text{loc}} + n \cdot m_{\text{wag}}) \cdot g \quad (3)$$

The stretch resistance force, that takes into account the road sloping, road curve radius, the rail-to-wheel friction and the mass of the wagon, could be found by (4), where $i$ is the road slope.

$$F_{\text{road}} = \sigma \cdot \left(m_{\text{loc}} + n \cdot m_{\text{wag}}\right) \left(\mu_i + \frac{i}{1000}\right) \cdot g \quad (4)$$

The aerodynamic force that depends on the velocity of locomotive and the number of wagons, could be calculated by (5), where $v$ is the velocity of locomotive and $A_{fl}$ is a frontal area of locomotive (Table I).

$$F_{\text{air}} = \frac{1}{2} \cdot \rho_{\text{air}} \cdot \left(C_{\text{loc}} + n \cdot C_{\text{wag}}\right) \cdot A_{\text{fl}} \cdot v^2 \quad (5)$$
The start-up overload for the rail road with slope of 10‰ is already with number of 20 wagons. But, the switching locomotive, usually, is not needed to start-up with such load on high slope, because they are usually operating at rail-stations and siding that were build without slopes. But sometimes switching locomotives operates in the classification yard, the place where the trains are putting together from wagons. The slope of classification yard could be up to 50 ‰ [9]. In that case the locomotive drive amain in the classification yard.

In Fig. 2, the road slope of 5‰ is presented. In that case the start-up overload is already with 30 and more wagons. Furthermore, in the area of high speeds and big number of wagons equal to 30. The start-up overload for the rail road with slope of 10‰ is already with number of 20 wagons. But, the switching locomotive, usually, is not needed to start-up with such load on high slope, because they are usually operating at rail-stations and siding that were build without slopes. But sometimes switching locomotives operates in the classification yard, the place where the trains are putting together from wagons. The slope of classification yard could be up to 50 ‰ [9]. In that case the locomotive drive amain in the classification yard.

In Fig. 2, the road slope of 5‰ is presented. In that case the start-up overload is already with 30 and more wagons. Furthermore, in the area of high speeds and big number of wagons (ca 35 wagons) the overload is also presented. The working area with a rail-road slope of 5‰ is quite wide, so the locomotive’s driver has a wide user options to operate the locomotive on a rail-road with slope of 5‰.

Fig. 2. Traction effort of switching locomotive ChME3 with rail-road slope 5‰.

In Fig. 3, the traction effort with a rail-road slope of 10‰ is presented. The working area of locomotive on Fig. 3 had a top in the point at velocity equal to 2 m/s and the number of

wagons dependence on the highest possible rail-road slope for defined power of a traction generator [2].

For the switching locomotives the value of velocity and the number of wagons (the load of locomotive) are very important. According to those parameters the driver of a switching locomotive is choosing the working mode of the locomotive. In ChME3 the driver operates with 8-position switcher that step-like add an additional resistance to exciting winding resistance of traction generator that changes the output power of generator that feeds the traction motors [2]. That mean the driver should chose the correct value of velocity according to number of wagons and rail-road slope. The diagram in Fig. 4 shows the velocity and number of wagons dependence on the highest possible rail-road slope for defined power of a traction generator. As it can be seen from Fig. 4, the rail road slope has significant affect at locomotives velocity and possible load. For example, the possible velocity with 20 wagons (mass of one waggon for that paper is 84 tones) is about 23 km/h and with the same load, but with a rail-road slope of 10 ‰ is only 5 km/h.

V. MAXIMAL POWER OF DIESEL ENGINE BASED ON THE TRACTION EFFORT LIMITS

The traction effort of traction motors of a switching locomotive is not the only thing that should be taken into account. The traction generator of the switching locomotive
has some critical level of power that should be taken into account to avoid the overloads.

Fig. 4. Velocity and number of wagons dependence from highest possible rail-road slope for defined power of traction generator.

The power of traction generator that is needed to provide the traction effort on the traction motors depends on the load on traction motors \( F_{\text{load}} \) (6), velocity of the locomotive \( v \), the total efficiency factor of locomotives traction system \( \eta_{\text{tot}} \) and power needed for the auxiliary devices \( P_{\text{aux}} \) (Table I). The traction generator power could be calculated by (12).

\[
P_{\text{diesel}} = F_{\text{load}} \cdot v \cdot \frac{1}{\eta_{\text{tot}}} + P_{\text{aux}}
\]

The maximal power that could be produced by the traction generator (13) and (14), could be found from the traction effort according to (9) and (10).

\[
P_{\text{max, dry}} = F_{\text{max, dry}} \cdot v \cdot \frac{1}{\eta_{\text{tot}}} + P_{\text{aux}}
\]

\[
P_{\text{max, wet}} = F_{\text{max, wet}} \cdot v \cdot \frac{1}{\eta_{\text{tot}}} + P_{\text{aux}}
\]

Similary to traction effort calculations, the worst atmospheric conditions should be taken into account. It means the maximal power with wet surface adhesive coefficient (\( \mu_{\text{wet}} \)) (14).

In Fig. 5 - Fig. 7 the maximal produced power of traction generator and the power needed to cover the load on traction motors are presented (Fig. 5 - Fig. 7 x-axe) with the different rail-road slopes. The number of wagons is presented on x-axe and velocity value on y-axe.

There are no road slope (0‰) in Fig. 5, the upper surface is the limit of a traction generatore and the lower surface is the power needed by traction motors to cover the load. As it can be seen from the diagramm, there is no any overload area in such bounds.

With a road slope of 5 %e there are already some overload area, the power diagram is present in Fig. 6. The overload area begins with the load of 30 wagons and the velocity of 24 km/h. The possible velocity of a locomotive is reducing if the load is increasing.

In Fig. 7, the traction generator power with the rail-road slope of 10%e is presented. In that case, the locomotive could not even start with the load of 30 wagons. The load limit with velocity of 24 km/h is 20 wagons.
VI. CONCLUSION

The paper presents the traction effort calculation method based on the switching locomotive ChME3 data. The Czech-origin switching locomotive ChME3 was chosen as an example because one third of switching locomotives used in Estonia is ChME3 that are already more than 30 years old and needs a modernizing. The current traction system of ChME3 consists of diesel engine and separately excited DC generator that feeds 6 series DC traction motors [2]. All parts of the traction system are obsolete and have a low efficiency factor. That kind of calculations is very important for locomotive motion planning. The motion planning of a switching locomotive should be done to avoid overloading during the working mode of a locomotive. The loads of locomotives are usually extra large, so the after-effects of overloads could be very dangerous.

The load on a traction system of locomotive depends on several parameters – the charge of wagons, the velocity of a train and the peculiar properties of the rail-road, the slope of rail-road and the curving radius of train are the most important.

Moreover, the worst weather conditions should be taken into account. Atmospheric condensations have a negative influence on the friction forces between the train wheels and rail-road rails.

That paper would be helpful for the future researches concerning to modernization of Estonian rail road.

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REFERENCES