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INCREASE OF TRACTION FORCES IN HEAD OF A TRAIN ABOVE CURRENT LIMIT IN THE NETWORK OF SPRÁVA ŽELEZNIC

ZVÝŠENÍ LIMITU TAŽNÝCH SIL V ČELE VLAKU NAD SOUČASNÝ LIMIT V SÍTI SPRÁVY ŽELEZNIC

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Abstract

Since the 1960s, a traction force limit at the head of the train of 350 kN has been applied on the Czech railway network. Compared to neighbouring countries, this limit is relatively low and negatively impacts freight transport efficiency. Therefore, Správa železnic initiated steps to revise relevant regulations and increase the traction force limit. One aspect addressed in cooperation with VÚKV during 2023–2024 was the interaction between vehicle and track and the running safety under traction forces exceeding 350 kN. The study began with theoretical analyses based on calculations and computer simulations of running dynamics. In the second phase, a test run was conducted with a train set capable of exceeding the current traction limit, with included an instrumented freight wagon equipped to measure key parameters (e.g., wheel forces via an instrumented wheelset and coupler forces at both ends). This paper summarizes the work carried out, key findings from the testing, and the resulting conclusions.

Keywords

traction force, screw coupler, safety against derailment, vehicle-track interaction, instrumented wheelset, freight transport, linear regression

Abstrakt

Již od 60. let platí na české železnici limit tažné síly v čele vlaku 350 kN. Tento limit je v kontextu sousedních zemí značně nízký a snižuje výkonnost zejména nákladní dopravy. Proto zahájila Správa železnic sérii činností vedoucích k novelizaci předpisů a zvýšení limitu tažné síly. Jedním aspektem, který byl řešen ve spolupráci Správy železnic a VÚKV v letech 2023 a 2024, byla interakce mezi vozidlem a tratí a bezpečnost jízdy při působení tažných sil nad 350 kN. Studium těchto oblastí bylo nejprve teoretické, založené na výpočtech a počítačových simulacích jízdy vozidla. V druhé části byla provedena jízdní zkouška se soupravou schopnou vyvinout tažnou sílu nad 350 kN, přičemž v soupravě byl zařazen instrumentovaný nákladní vůz, na němž byly měřeny relevantní veličiny (např. kolové síly na všech kolech prostřednictvím měřicího dvojkolí, síly ve spřáhlech na obou koncích).

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Tento příspěvek se zabývá shrnutím těchto provedených prací, poznatků z provádění a závěrů těchto prací.

Klíčová slova

tažná síla, šroubovka, bezpečnosti proti vykolejení, interakce vozidlo-cesta, měřicí dvojkolí, nákladní doprava, lineární regrese

1 INTRODUCTION

The current state regarding the maximum traction force at the head of the train in the Czech Republic (specifically on the Správa železnic network) dates back to the 1960s (see Regulation D 12 of 1962 [1] and later D 2/1 [2]). At that time Czechoslovak railway faced a critical situation with an extreme number of screw coupler ruptures (circa 2 600 in 1960). This led to a thorough investigation into the causes of these failures and the development of solutions to mitigate them. The main reason identified was the longitudinal dynamics within a train set when traction and braking forces were exerted. To eliminate the risk posed by traction forces, a traction force limit was introduced. Based on experimental analysis, a limit of 350 kN at the head of the train was established [3], and this limit remains unchanged to this day [2].

However, this limit is now considered low. It restricts the effective use of modern locomotives, especially when two are positioned at the front of the train. It has been demonstrated that longitudinal dynamics are no longer critical with respect to screw coupler strength [4]. Similar conclusions can be drawn from the situation in other European countries. Summary of the limits is given in Tab. 1. This overview highlights the need to increase the traction force limit in the Czech Republic.

Tab. 1 Overview of the traction forces in head of train in selected European countries [5]

Country	Limit
Czech Republic	350 kN
Slovakia	No explicit limit • Until 2006: 350 kN
Austria	450 kN • Can be individually increased
Germany	No explicit limit • Limited with “operational strength of the coupler” • Until 2021: 450 kN for 1.0 MN screw coupler, 500 kN for 1.2 MN screw coupler
Poland	No explicit limit
Hungary	No explicit limit

These findings concern only the vehicle side (screw coupler strength) and existing regulations. Another crucial aspect is the interaction between the vehicle (subjected to traction force) and the infrastructure. Moreover, we shall concern running safety of such vehicle. A coupler's force applied to a vehicle in a curved track alters the distribution of the guiding force Y and the vertical force Q. This study addresses:

1. quasistatic changes in wheel force during curving,
2. dynamic changes in wheel forces during run through S-curves (crossovers).

Accordingly, the study investigates the behaviour of a representative train set subjected to traction forces while passing through simple curves and S-curves.

2 THEORETICAL STUDY

Theoretical analysis was conducted using analytical calculations and numerical simulations. The primary objectives were:

1. preliminary assessment of running safety,

2. identification of critical phenomena and definition of evaluation metrics,
3. instrumentation requirements,
4. investigated train set composition,
5. track alignment determination.

Simplified analytical model of a three-wagon train set in a curve was developed. The outer wagons induce angular misalignment in the screw couplers, generating $F_{\mathrm{t,y}}$ (lateral components of traction force F_{t}) on the middle wagon (see Fig. 1).

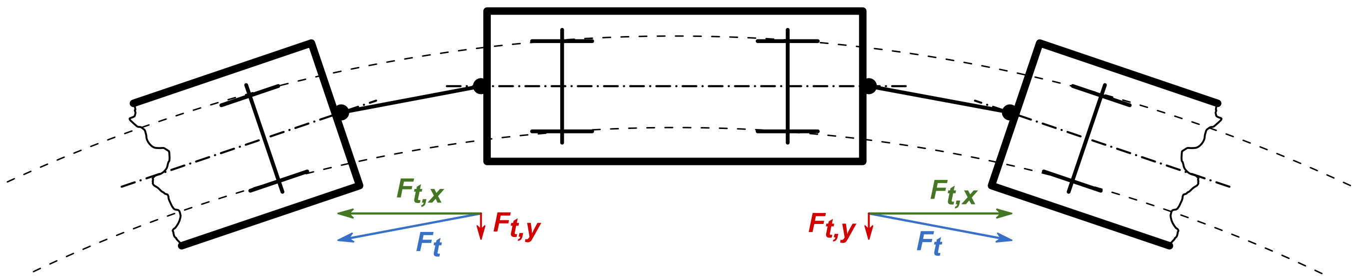

Fig. 1 Principle of generation of the lateral component of the coupler force

This lateral force redistributes *Q* forces, causing wheel unloading on one side of the wagon. As traction increases, the unloading becomes more severe and may approach the $(Y/Q)_{\mathrm{lim}}$ criterion or even lead to overturning. A sensitivity analysis identified the following.

1. maximum $F_{\mathrm{t,y}}$ occurs with combination “short wagon with short overhang” + “long wagon with long overhang”;
2. minimum $F_{\mathrm{t,y}}$ occurs for combination of similar wagons;
3. on the front end of the wagon is the maximum $F_{\mathrm{t,y}}$, on rear end of the wagon is the minimum $F_{\mathrm{t,y}}$;
4. lower the own weight of the wagon the relative wheel unloading Δq is more significant;
5. tighter the curve the $F_{\mathrm{t,y}}$ is larger.

The train set configuration fulfilling these criteria is: Shimmns + **Sggnss 80’** + Sggnss 80’, where **bold indicates the investigated wagon**. This composition of the train set was selected among other 15 compositions. Wagon classes were selected accordingly to standard freight operation in Czech Republic.

MBS simulations using rigid body models (see Fig. 2) with detailed bogie suspension model, draw gear and buffers with hysteresis suspension and spherical buffer contact were performed for several traction force magnitudes. With this model, simulation scenarios with different magnitude of the traction force were calculated. The scenarios in simple curves catch sensitivities on cant deficiency, radius of 250 m was selected as the common minimum radius on main lines. For S-curves radii of 190 m and 300 m were selected. Radius 190 m is one of the least possible and corresponds to alignment in standard [6]. Radius 300 m is presumed as common minimum on main lines. Správa železnic performed a thorough analysis of track alignment in order to find all S-curve with radius less than 300 m and intermediate straight shorter than 8 m (without crossovers). All 26 found track sections were located on local lines without extensive freight transport. Simulations were run for empty wagons. Parameters are given in Tab. 2.

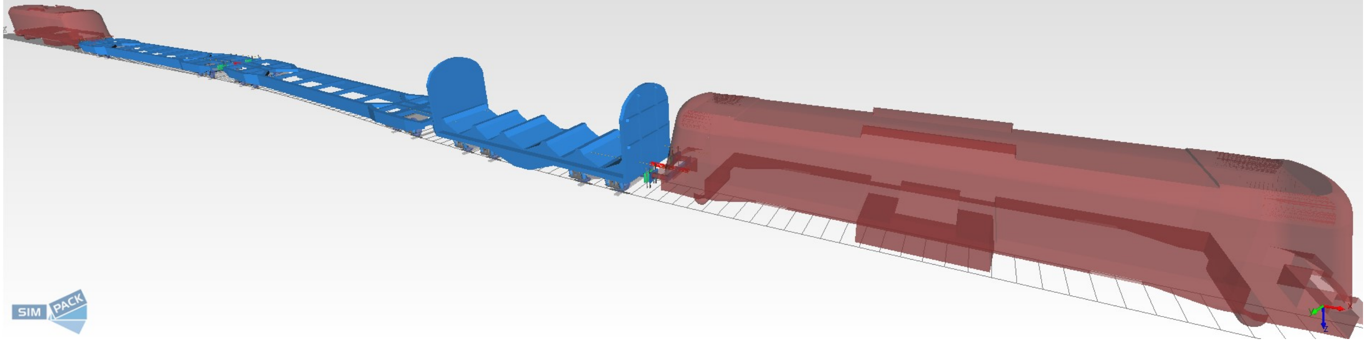

Fig. 2 SIMPACK visualisation of the model; composition: pulling body + Shimmns + 2x Sggnss 80’ + braking body

Tab. 2 Overview of parameters of performed simulations

Track alignment	Radius [m]	Intermediate straight Length [m]	Speed [km/h]	Traction force [kN]
Simple curve	250	---	56 (balanced speed)	0; 350; 500
Simple curve	250	---	21; 33; 46; 56; 65; 73	500
S-curve	190	5	10	0; 350; 500
S-curve	190	5; 7; 8; 9; 11; 14	10	500
S-curve	300	7; 8; 9; 11; 14	10	500

Criteria were primarily based on [7]. Overview is given in Tab. 3 (other quantities from [7] has been shown as non-significant). The Prud'homme criterion for the limit of sum of guiding forces ΣY_{max} seems too restrictive, so an alternative from [6] was adopted. A minimum wheel force Q_{min} limit was also added to the criteria set. This quantity describes the risk of overturn.

Tab. 3 Criterion overview used for evaluation

Quantity	Abbr.	Criterion	Description
Minimum vertical wheel force	Q_{min}	$> 0.1 \cdot Q_0$	Wheel unloading
Maximum ratio of wheel forces	$(Y/Q)_{max}$	< 0.8 (simple curve) < 1.2 (S-curve)	Safety against derailment
Maximum sum of guiding forces	ΣY_{max}	$< 0.85 \cdot (2Q_0/3 + 10\ \mathrm{kN})$	Prud'homme acc. [7], informative
		$< 0.6 \cdot 2Q_0 + 25\ \mathrm{kN}$	Prud'homme acc. [6]

Results showed that the most critical case was a simple curve with maximum cant excess. This scenario corresponds for example to setting the train set in motion. The Q_{min} criterion on outer wheels proved to be a limiting factor, partly due to its conservative nature as it is applied per wheel. The worst results for simple curve for Q_{min} and ΣY_{max} are shown in Fig. 3 and Fig. 4. From these we can conclude that the operation should be safe up to traction force $F_t = 500\ \mathrm{kN}$.

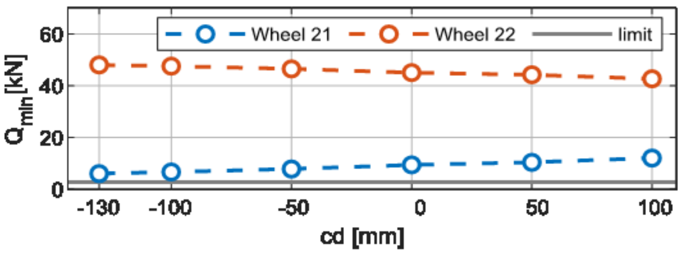

Fig. 3 Dependence between Q_{min} and cd in simple curve, Wheelset 2, $F_t = 500\ \mathrm{kN}$, outer wheel 21

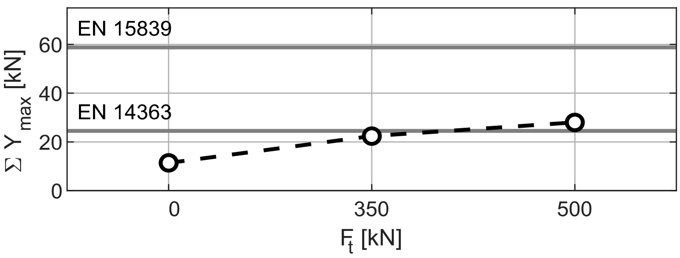

Fig. 4 Dependence between ΣY_{max} and traction force F_t in simple curve, Wheelset 2, $cd = 0\ \mathrm{mm}$

For S-curves, Q_{min} remained close to the limit at 190 m radius even with long intermediate straight L (Fig. 5). On the contrary, 300 m was found safe (Fig. 6). Hence, experiments were limited to S-curves with radius ≥ 300 m.

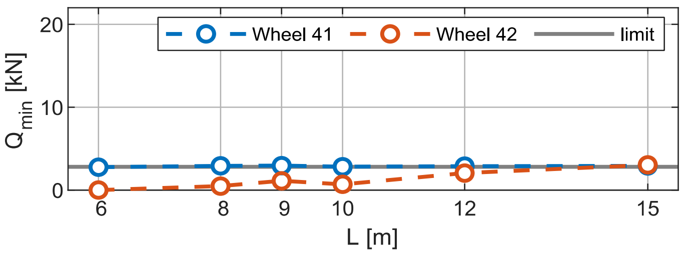

Fig. 5 Dependence between Q_{min} and L in S-curve of radius 190 m, Wheelset 4, $F_t = 500\ \mathrm{kN}$

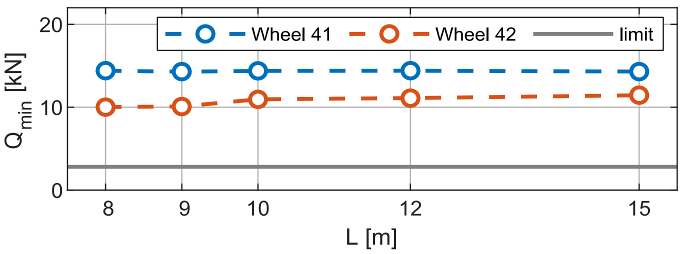

Fig. 6 Dependence between Q_{min} and L in S-curve of radius 300 m, Wheelset 4, $F_t = 500\ \mathrm{kN}$

3 EXPERIMENTAL STUDY

3.1 Design of Experiment

Requirements for the experiments and solutions are summarised in Tab. 4.

Tab. 4 Summary of requirements for the experiments

Requirement	Implementation
Train set must achieve 500 kN traction force and maintain it on a constant level.	Two Class 193D ČD electric locomotives (320 kN each) were used for traction. Four Class 363.5 ČD Cargo locomotives, each providing 160 kN of braking force via EDB, ensured speed regulation.
The train set composition is: Shimmns (front wagon in running direction) + Sggnss 80' (instrumented wagon) + Sggnss 80'.	The train set composition is: Eamnoss + Sggnss 80' + Sggnss 80' (Fig. 7); Shimmns was replaced by a similar Eamnoss wagon due to better availability.
The instrumented wagon has to be able to provide data of all relevant quantities.	The instrumentation is shown on Fig. 8. The instrumented wagon was equipped to measure all relevant quantities, including inter-wagon forces and wheel forces, using four instrumented wheelsets and additional sensors in compliance with [7].
The track shall consist of range of curves' radii 250 m up to 500 m with sufficient length.	The track line 502A, sections Golčův Jeníkov – Leština u Světlé and Okrouhlice – Havlíčkův Brod were selected. These cover Zone 3 and Zone 4 according to [7].
The track shall consist of S-curves with radius 300 m and the shortest possible length of intermediate straight.	In the station Vlkaneč in the section Golčův Jeníkov – Leština u Světlé there is a crossover with radius 300 m and intermediate straight 9,49 m long.
The experiments shall be done for maximum permissible speed on the track (maximum dynamic forces); minimum possible speed (maximum possible cant excess).	The experiments were performed for the maximum permissible speed (cant deficiency 100 mm) and for speed between 25 km/h and 35 km/h.

Fig. 7 Photography of the train set consisting of: 2x 193D + Eamnoss + **Sggnss 80'** + Sggnss 80' + 4x 363.5

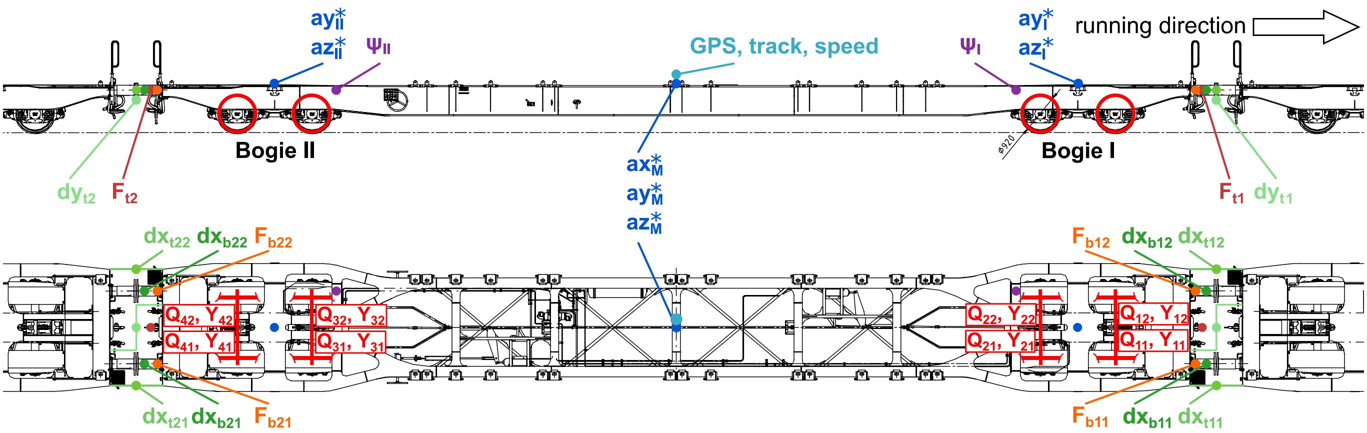

Fig. 8 Scheme of the instrumentation of the middle Sggnss 80' wagon

The evaluation is divided to two parts: evaluation of running through curves and evaluation of running through S-curve. Both parts are evaluated statistically with linear regression. The principle is similar to the evaluation of the dynamic performance assessment according to [7]. The input data are processed (according to the [7]). They are categorized by curve type and divided to evaluation sections (simple curves are cut to sections of length 70 m, for S-curves the section is over their overall length). Moreover, the sections in simple curves are categorized according to radius (same as division to Zones in [7]). In each evaluation section, if all required boundary conditions are met (e.g. minimum variability in the traction force, speed, cant deficiency), the characteristic values for all quantities are calculated. For each set of characteristic value of quantity linear regression was calculated (in dependence on traction force and cant deficiency for curves; in dependence on traction force for S-curves). Then the prediction intervals were calculated with a confidence level 99 % for the simple curves. An intersection between the prediction interval for maximum admissible cant excess ($cd = -150\ \mathrm{mm}$) and the limit value defines the admissible traction force $F_{\mathrm{t,adm}}$. For the S-curves, the set of usable sections for evaluation is lesser, therefore no prediction intervals were calculated and $F_{\mathrm{t,adm}}$ is determined from an intersection between a regression line and the quantity limit value. The value of $F_{\mathrm{t,adm}}$ is calculated for all quantities. The lowest value from the set of $F_{\mathrm{t,adm}}$ defines the limit value to traction force $F_{\mathrm{t,lim}}$.

The used limit values of quantities are the same as in the theoretical study (see Tab. 3). However, we replaced the extremely restricting criterion for Q_{min} with sum of the vertical wheel forces on one bogie side ΣQ_{min}. This quantity better captures the possibility of overturn, although still conservative with enough margin to physical overturn. The limit value for ΣQ_{min} is $0.1 \cdot P_{\mathrm{F0}}$, where P_{F0} is static wheelset loading.

3.2 Experiment Results

Results for Simple Curves

First part considers running through simple curve. The quantity giving the lowest value of $F_{\mathrm{t,adm}}$ is ΣQ_{min} on outer wheels. Other quantities according to [6, 7] were proved not to be as critical. The resulting permissible traction forces calculated for each range of curve radii are in Tab. 5. Results with lowest admissible traction force are depicted in Fig. 9. The cant deficiency and traction force are well covered. Achieved maximum traction force is around 500 kN. The dispersion around regression line of results for $\Sigma Q_{\mathrm{min,rec}}$ (values of vertical wheel force sum recalculated on $cd = -150\ \mathrm{mm}$ with use of the regression coefficient) is not significant. This indicates great stability and reliability of the results. Prediction interval intersects with the limit value at $F_{\mathrm{t}} = 730\ \mathrm{kN}$.

Tab. 5 Overview of limit traction forces in dependence on curve radius

Curve radius range	Mean radius value	Number of sections	Limit traction force	Note
$250\ \mathrm{m} \leq R < 300\ \mathrm{m}$	275 m	280	730 kN	Main range to eval.
$300\ \mathrm{m} \leq R < 350\ \mathrm{m}$	325 m	27	780 kN	
$350\ \mathrm{m} \leq R < 450\ \mathrm{m}$	400 m	81	> 1000 kN	
$450\ \mathrm{m} \leq R < 600\ \mathrm{m}$	525 m	38	> 1000 kN	
$600\ \mathrm{m} \leq R$	---	---	---	No sections

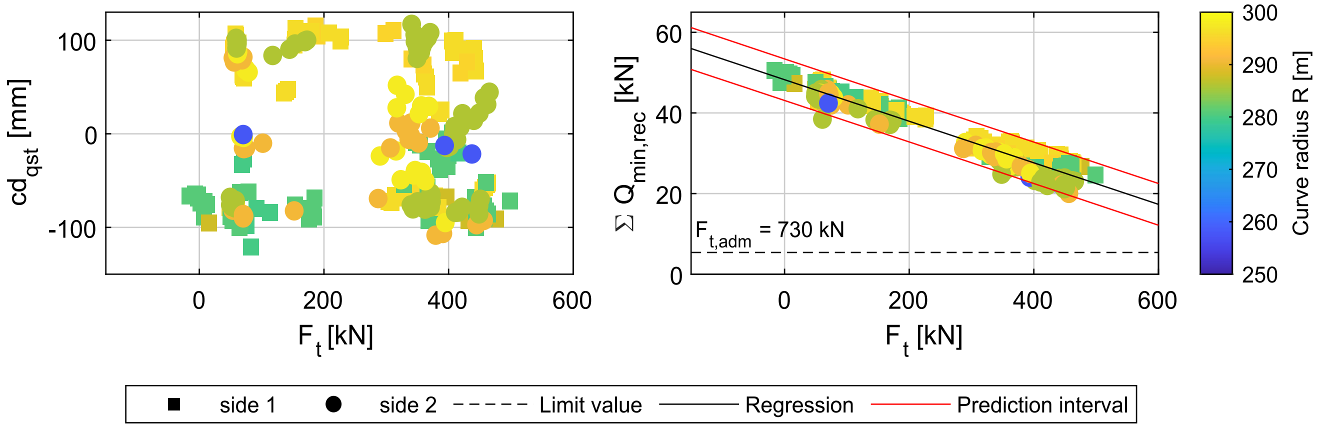

Fig. 9 Results for $\Sigma Q_{\min}$ for selected bogie, left: map of data set with respect to the traction force and the cant deficiency; right: regression for recalculated quantity to $cd = -150$ mm in dependence on traction force

Results for S-curves

For evaluation of the S-curve the statistical set is lesser as for simple curves. The lowest possible value of traction force is given by the criteria for $(Y/Q)_{\max}$ and $\Sigma Q_{\min}$. However, particularly $(Y/Q)_{\max}$ is distorted with significant dynamic effects when the wheel is passing over frogs. The results are in Fig. 10. Even under these conditions the maximum permissible traction force is above 870 kN.

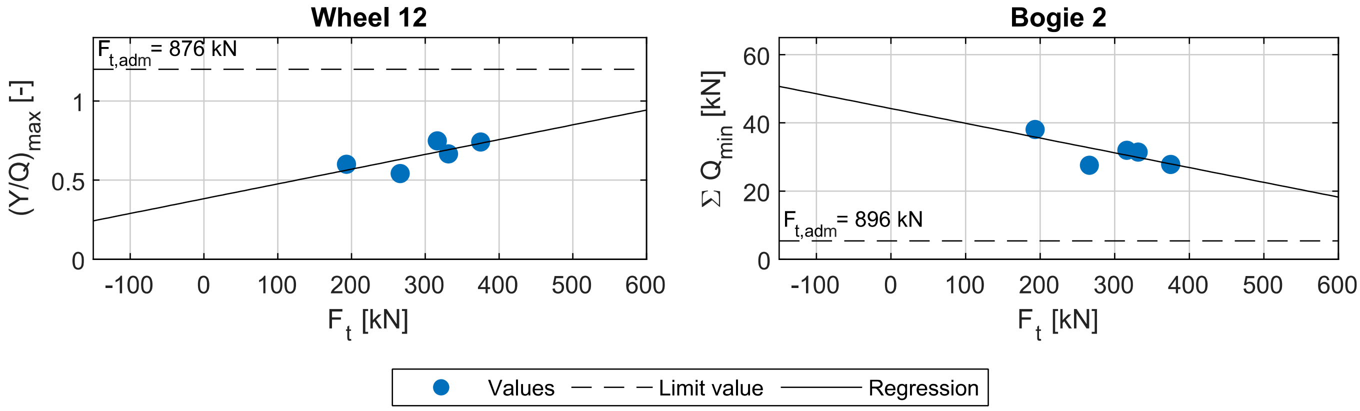

Fig. 10 Results for $(Y/Q)_{\max}$ and $\Sigma Q_{\min}$ in S-curves

4 REMARKS AND CONCLUSION

The presented analysis shows that the limit can be increased above current limit 350 kN and Správa železnic proceeds with necessary steps to its change. There is a discussion upon the new limit value which has to fulfil following boundary conditions. Possible proposed safe value is 450 kN.

- The limit has to be under value 730 kN. This is the lowest admissible value according to the experiments.
- The limit applies for track sections with allowed two bank locomotives as in Tables of Track Conditions (*TTP – Tabulky traťových poměrů*). This follows from requirements for the minimum curve radius 250 m and two bank locomotives are permitted only in curves with radius 250 m and greater.
- The limit applies only for crossovers with radius higher or equal than 300 m (lower radii were not investigated). Thus, the limit applies only for stations with indicated speed above 50 km/h.
- State of a track is suitable for normal operation according to Tables of Track Conditions. If there is any deviation in track quality affecting interaction with a vehicle the limit can be locally reduced.
- In a case of favourable conditions (quality, track alignment) the limit can be locally increased based on an expert opinion.

However, from measured data we can conclude other interesting findings.

- The quality of the track can have significant influence on the Q force, even if there is no apparent defect. In a few track sections significant periodicity in vertical irregularities led to wheel unloading, ultimately in combination with higher traction force to a wheel lifting.
- Although weather during testing was acceptable (partly cloudy, dry rails) the locomotives had problems to exert its maximum traction force. Especially in curves a significant lateral creepage caused substantial decrease in traction force.
- These observations do not necessarily apply only to the standard UIC coupling (screw coupler with buffers), but its nature (generation of a lateral force with respect to a vehicle axis in a central pulling element when curving) also applies to any central coupler (e.g. DAC – Digital Automatic Coupler). Therefore, the consequences of these experiments shall be also reflected for the DAC.
- As the traction force in curve changes distribution of the Y forces, wear between rail and wheel also changes. According to a MBS simulation, Wear Number (describing dissipated energy in a rail-wheel contact responsible for wear) for an empty wagon rises about 25 % for traction force 400 kN.

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