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ON SIMULATION OF WHEEL/RAIL WEAR IN METRO OPERATION

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Abstract

Wheel and rail wear is extremely intensive in metro operation due to the high frequency of the regular train passages on the rails and to the intensive acceleration and deceleration of metro cars. In this paper, the results of a computer based complex analysis concerning the wear propagation vs. covered distance in case of wheels, or vs. contact frequency in case of rails, respectively, will be dealt with. The forces and velocities characterising the metro train operation on specified metro lines are determined by using the real-time simulation program TRAINSIM. The simulation results appear in form of tractive/braking effort and velocity distributions for the straight and curved track sections of the considered metro railway line. Wheel and rail wear propagation is treated by using simulation program system ELDACW, which takes into account the lateral track irregularities, as well. The wear simulation results in worn wheel and rail profiles as a function of the duration of the operation process considered. Based on the latter simulations, a comparative analysis is carried out to select the advantageous metro vehicle parameters. The objective function of the intended maximisation is the mileage performance of metro trains. The action parameters of the analysis are the longitudinal and lateral axle-box guidance stiffnesses, as well as the initial wheel profiles. The study gives recommendations to achieve increase in mileage performance.

Keywords: dynamical simulation of metro trains, wheel/rail profile wear simulation, parameter optimisation.

1. Introduction

Wear of wheels and rails contributes considerably to the total operation and maintenance costs of railway systems. Wheel and rail wear is especially intensive in metro operation due to the high frequency of the regular train passages and to the very intensive tractive and braking effort exertions in the course of acceleration and deceleration of the trains. In this study, the results of a computer based complex analysis are introduced, which was carried out to predict chiefly the wheel profile wear propagation vs. distance covered in the Budapest metro operation. To ensure realistic rail profiles for the wheel profile wear simulation, an extended pre-simulation of rail profile wear propagation was carried out based on the worn wheel profiles received from the results of an initial wheel profile wear simulation, the latter is taking new rail profiles into consideration. The average tractive/braking forces and travelling velocities characterising the metro train operation in different curved and straight sections of the two Budapest metro lines were determined by using the real-time simulation program TRAINSIM [1]. With the knowledge of the average forces and velocities mentioned, the wheel and rail wear propagation was treated by using the simulation program system ELDACW [2, 3, 4]. On the basis of the results of wear simulations in the framework of a sensitivity analysis, a comparison was made to select more advantageous metro vehicle running gear parameters that can ensure higher mileage performance values.

2. Generating Tractive and Braking Efforts and Operation Speeds by Train Motion Simulator

The forces and velocities characterising the metro train operation on the Budapest metro lines are determined by using the real-time simulation program TRAINSIM [1]. The latter program requires the tractive effort vs. velocity and braking force vs. velocity diagrams of the powered units. In *Fig. 1*, the tractive effort and braking force diagrams are shown for the three vehicle types used on the Budapest metro lines, namely types EV, EV3 and 81. This sequentiality reflects also the increase in rated power. There are slight differences in the running gear construction of the three vehicle types mentioned.

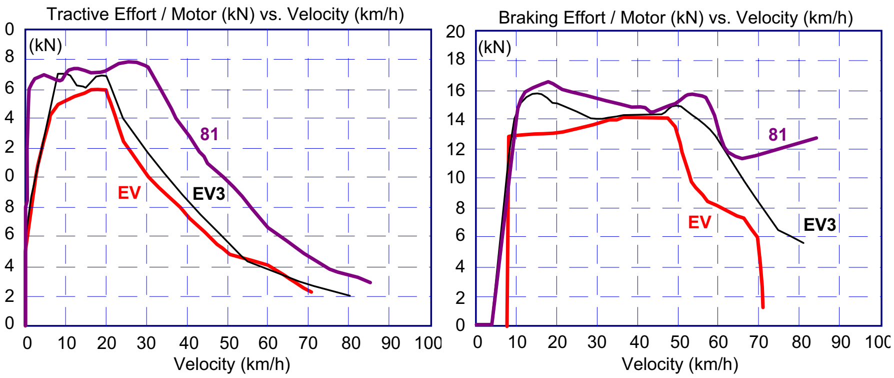


Fig. 1. The tractive effort and braking force vs. velocity diagrams

For the simulation, also the track profiles and the curvature data were required for the two metro lines considered. The total length of the East – West line is 10.4 km with 11 stops, and the total length of the North – South line is 17.3 km with 18 stops, included terminals. The maximum permitted velocities were also specified by track arc-length-dependent step functions for both lines.

2.1. *Results of the Simulation Using TRANSIM*

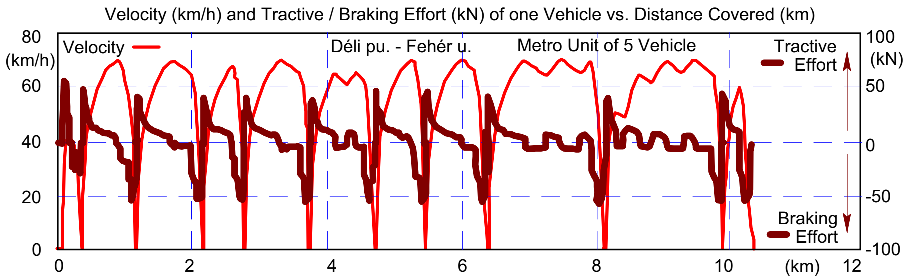
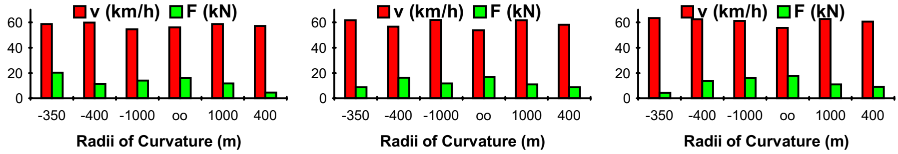


Fig. 2. EV Vehicle on the East – West line

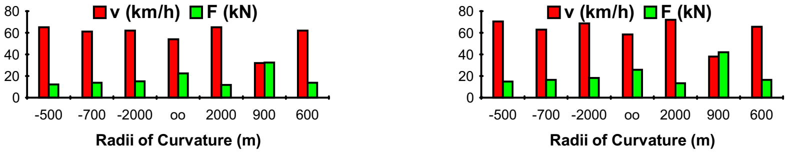
The simulated train motion appears in velocity vs. distance covered and tractive/braking effort vs. distance covered diagrams, see *Fig.* 2. The evaluation of the direct simulation results leads to average tractive/braking effort and average velocity distributions for the straight and curved track sections of the two metro lines considered. In *Fig.* 3, the characteristic column diagrams show the mentioned distributions indicating the average tractive/braking force and average velocity conditions belonging to the essential radii of curvatures being present in the two Budapest metro lines and for the vehicle types operating on the latter.



Type EV, East - West

Type EV3, East - West

Type 81, East - West



Type EV3, North - South

Type 81, North - South

Fig. 3. Average tractive/braking effort and average velocity distributions

3. Pre-Simulations to Determine Worn Wheel/Rail Profiles

With the knowledge of the simulated average forces and velocities mentioned, the wheel and rail wear propagation is treated by using the simulation program system ELDACW (Excited Lateral Dynamics, Arbitrary Curving and Wear), which takes into account the lateral track irregularities, as well [2, 3, 4].

The lateral track irregularity realisations were determined by a new identification procedure based on measured track irregularity functions. The latter were measured by means of a measuring chord system (gauge and lateral non-alignment). As it is known, the measurement results coming from the measuring chord system are biased. To achieve non-biased excitation realisation functions, a simulation-based identification procedure was elaborated. The identification of the excitation realisation functions was carried out both for 300 m track length in straight sections while for 50–300 m track length in curved sections of constant radius.

All identified track sections (straight or curved) were partitioned in 2–12 consecutive track intervals of about 20–40 m length each. In each simulation step of the material removal due to wear, one realisation function of 20–40 m length was randomly selected for each straight and curved section as representative, where the selection of realisation function sections obeys the uniform probability distribution.

The distributions characterising the track curvature conditions are shown in *Fig. 4*. The figure contains the accurate track length values belonging to the curvatures really existing in the considered metro lines (dark thin columns), while the integrated track length values taken into account during simulations are indicated in the figure by thick grey columns. It is to be mentioned that the latter track lengths were joint to the real track curvature values being the nearest neighbour of the weighted average of the curvatures falling into a class of integration.

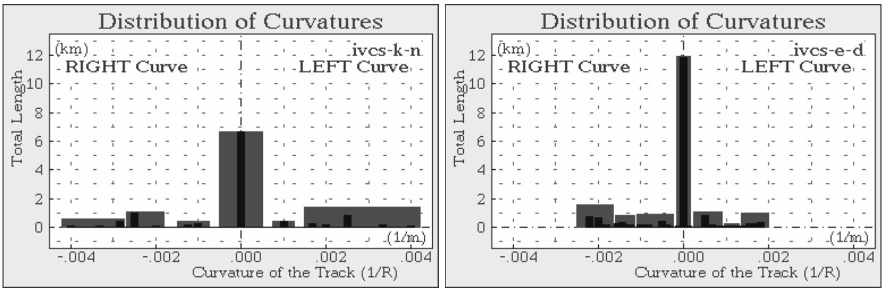


Fig. 4. Length-fraction distributions of track curvatures and their integration for the simulations

3.1. Simulation of the Wheel Profile Wear Based on the New Rail Profiles

In order to ensure realistic medium and total worn wheel profiles for the further generation of the worn rail profiles, a sequential simulation was carried out concerning the operation of EV type metro trains on the East - West line under the condition of wear-free rail profiles. In the course of the simulation procedure, the prescribed mass removal was 0.2 kg in each simulation step.

The results of the pre-simulation procedure for initially wear-free rail and wheel profiles (‘new-new’) are shown in *Fig.* 5. The received mileage performance (i.e. the total distance covered up to the exhaustion of the permitted limit dimensions of the profiles) was 16 500 km. The cause of the exhaustion of the limit dimensions was the excessive decrease in flange width.

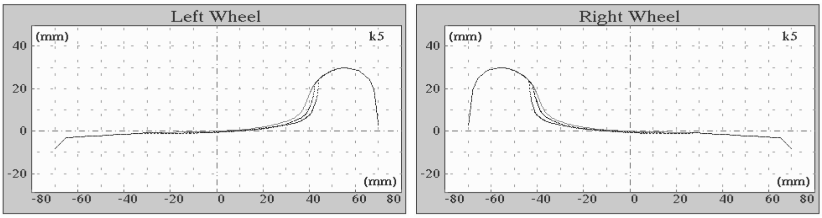


Fig. 5. Medium worn and severely worn wheel profiles for the rail wear simulation

Profile alteration due to wear appeared major on the flange. The tread wear did not achieve 1 mm. The results are in accordance with the intensive flange wear experienced initially in the Budapest Metro operation.

3.2. Simulation of the Rail Profile Wear Based on the Worn Wheel Profiles

On the basis of worn wheel profile curves received from the pre-simulation, the rail profile wear was determined by means of simulation on the selected track sections with the intent of generating worn rail profiles for further simulations.

In the course of the simulation, vehicle type EV3 was taken into consideration. As for the wear conditions of the wheel profiles used, the following proportions were taken: 25% severely worn, 50% medium worn and 25% wear-free (new) profiles were involved. The rail profile type considered was MÁV 48 for the track sections of the East – West line while UIC 54 type for the track sections of the North – South line. The results of the simulation for track sections of North – South line are shown in *Fig.* 6 and for those of the East – West line are shown in *Fig.* 7.

4. Wheel Profile Wear Simulations on Metro Tracks of Worn Rails

On the basis of the results concerning wear propagation on the rail heads described in the previous chapter, there was no obstacle to carry out the final simulations to determine the wheel profile wear propagation under realistic operation conditions of the metro service. The results of the final wear simulation received by using the rated (nominal) parameters of vehicles of type EV, EV3 and 81 appear in worn wheel profiles shown in *Figs. 8*, *9* and *10*, as functions of the actually covered distance realised in the course of the considered operation process on the East – West line.

In *Fig. 11*, the evaluation of the so called partial mileage performances is shown in column diagram representing the values of total distance covered up to achieving three selected profile dimensions, namely those of the 2.5 mm radial tread wear on the running circle (k_25b, k_25j), the 30 mm flange thickness at 10 mm distance over the running circle (n_30b, n_30j) and the 27 mm flange thickness at the same distance from the tread (n_27b, n_27j).

Similarly, the wheel wear propagation results received by using the rated parameters of a vehicle of type EV3 and 81 are shown in *Figs. 12*, *13* and *14* for the North – South line.

As it can be read off the Figures, the wheel flange wear process is more intensive with the left hand side flanges due to the more frequent passage of right hand side curves of greater curvature in the course of the regular operation on the metro lines considered. Accordingly, more intensive tread wear can be observed on the right hand side wheels. The asymmetry occurring in the right and left worn wheel profiles can also be traced back to the mentioned circumstances concerning the track curvature conditions.

As regards the intensity of wear conditions of the vehicles operating on the East – West line, it can be recognised that initially the flange wear on the right wheels is mild, while with the increase of the distance covered, the flange wear becomes considerably more intensive in comparison with the more or less uniform flange wear propagation on the left wheels. At the same time, it can be seen that the intensive flange wear on the right wheels is in correlation with a significant deviation in the tread wears of both wheels.

5. Sensitivity Analysis of Running Gear Parameters

On the basis of the results of wear simulations, a comparative analysis was carried out to select the advantageous running gear parameters of the metro vehicles in question. The considered *objective function* with the intent of possible maximisation of the mileage performance of metro trains was the total distance covered by the vehicles up to the exhaustion of the permitted wheel profile dimensions. The *action parameters* of the analysis were the longitudinal and lateral stiffnesses of the axle-box guidance, as well as the type (K5 and K6) of the initial wheel profiles.

5.1. *Analysis of Longitudinal Axle-Box Guidance Stiffnesses*

The influence of longitudinal axle-box guidance stiffness exerted on the partial mileage performances introduced before is shown in *Figs.* 15–17 for the vehicle types operating on the East – West metro line. The 100% stiffness values belong to the original layouts.

For the North – South metro line, the characteristic partial mileage performance diagrams are shown in *Fig.* 18 and *Fig.* 19.

As it can be read off the diagrams, in case of increasing longitudinal axle-box guidance stiffnesses, the tread wear is of increasing tendency, while the flange wear is slightly increasing mainly at the right wheels and decreasing mainly at the left wheels. With increasing longitudinal axle-box stiffnesses, the differences between the left and right wheel profile wears are also of increasing tendency.

5.2. *Analysis of Lateral Axle-Box Guidance Stiffnesses*

The influence exerted by the lateral axle-box guidance stiffness on the partial mileage performances introduced before is shown in *Figs.* 20–22 for the vehicle types operating on the East – West metro line. Similarly, for the North – South metro line, the characteristic partial mileage performance diagrams are shown in *Fig.* 23 and *Fig.* 24. The 100% stiffness values belong to the original layouts.

With increasing lateral axle-box guidance stiffness, tread wear is slightly increasing, while flange wear shows a decreasing tendency (except vehicle type 81 on the North – South line). There are again non-negligible differences between the left and right worn wheel profiles, that can be traced back to the quantitative deviations in the lengths and radii of the right and left curves in the considered metro lines.

5.3. *Analysis of the Influence of Initial Wheel Profiles*

In order to get insight into the influence of the initial wheel profile versions, two kinds of familiar wheel profiles were reckoned with. The original profile used in the Budapest metro service is that of K5. The alternative profile version is profile K6, which has the same internal geometrical conditions, but the whole profile is shifted laterally by 2 mm towards the gravity centre of the wheelset. Accordingly, the total initial clearance increment between the flanges and rail heads is 4 mm. Due to the mentioned 2 mm lateral shift per profile, when comparing the flange wear conditions, the distance covered belonging to the event of exceeding a lateral flange width of 27 mm valid for profile K5 was compared to the distance covered belonging to the event of exceeding a lateral flange width of 25 mm in case of profile version K6. In the column diagrams below the latter case is designated by n_27,25b and n_27,25j, respectively.

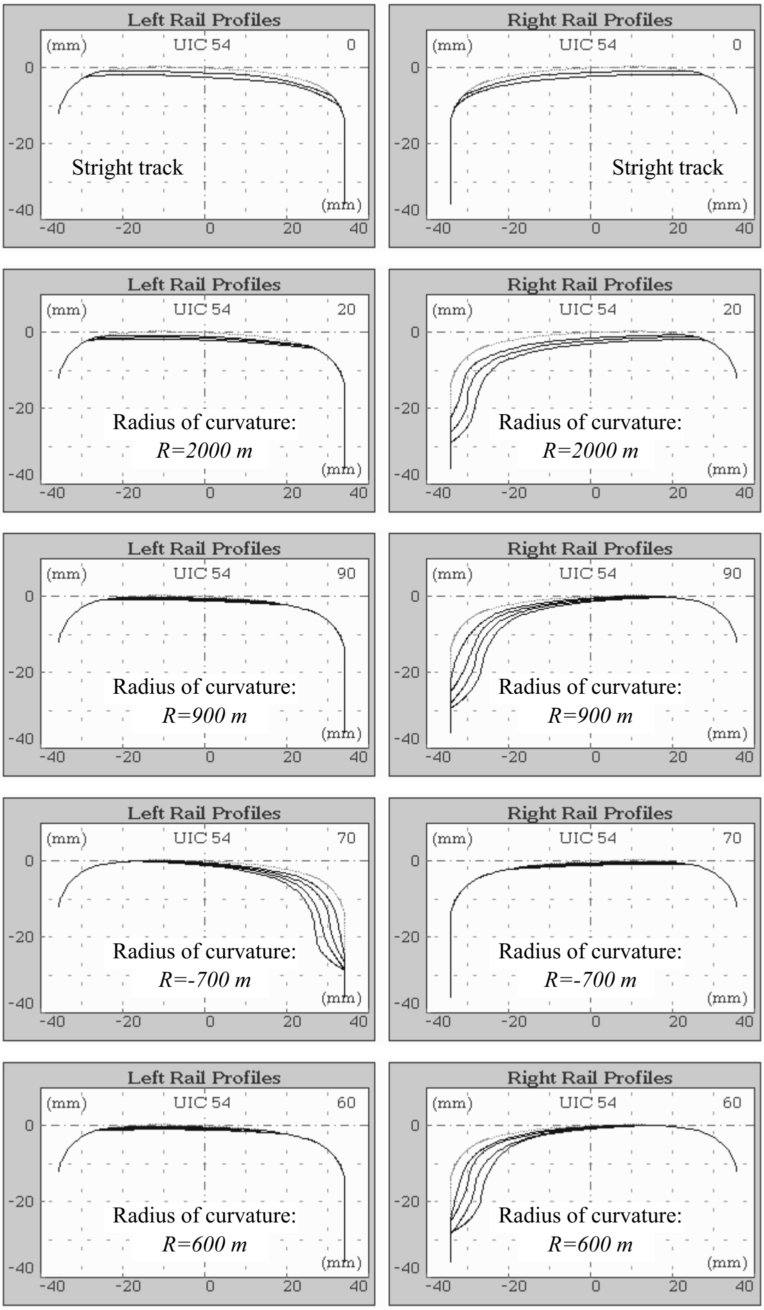


Fig. 6. Worn rail profiles, Metro line: North – South

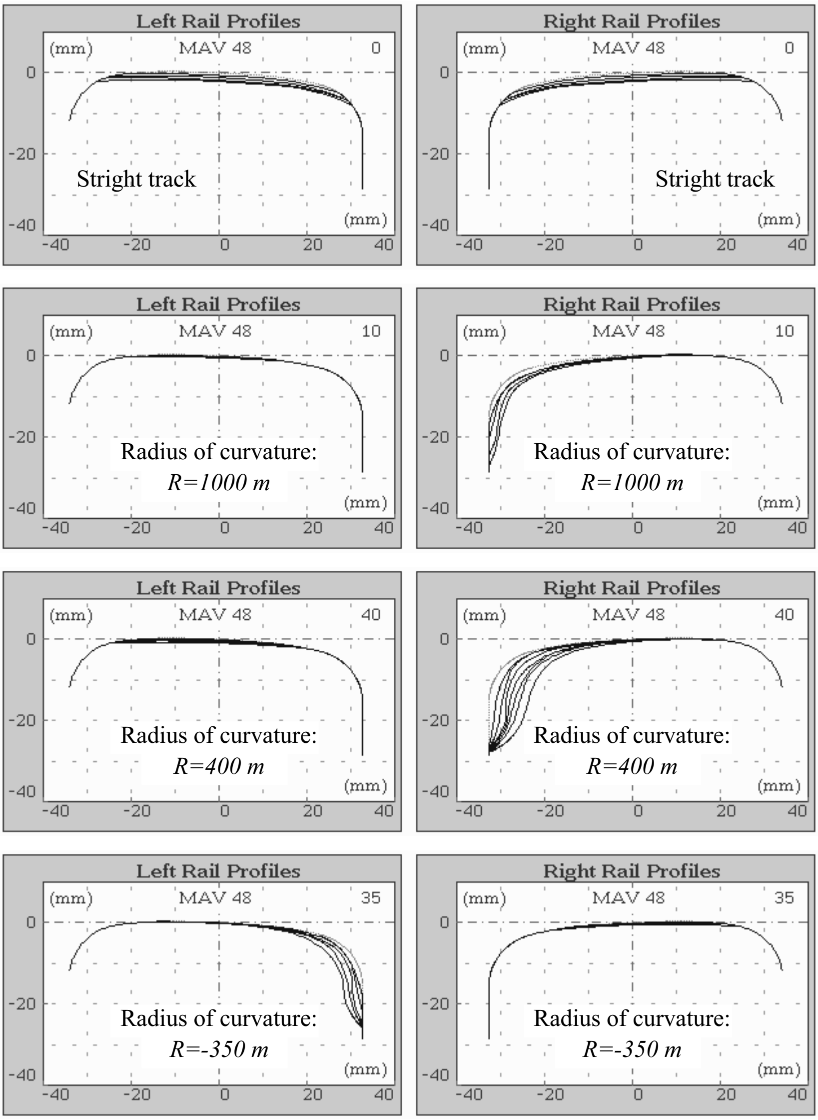


Fig. 7. Worn rail profiles, Metro line: East – West

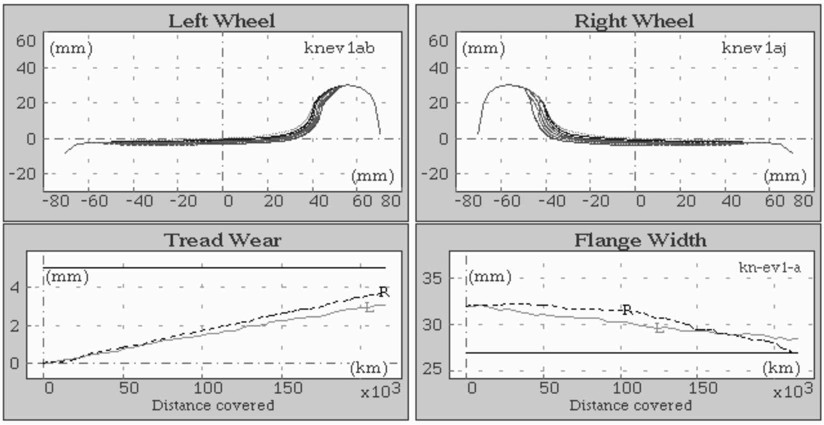


Fig. 8. Wheel wear process of a vehicle type EV, on the East – West line

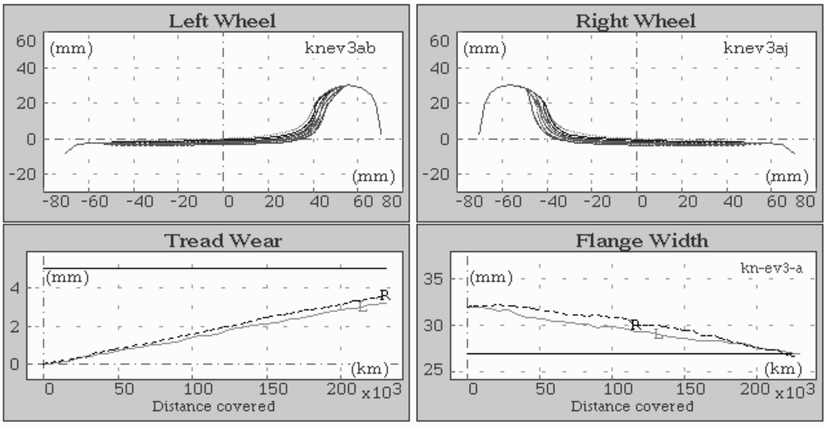


Fig. 9. Wheel wear process of a vehicle type EV3, on the East – West line

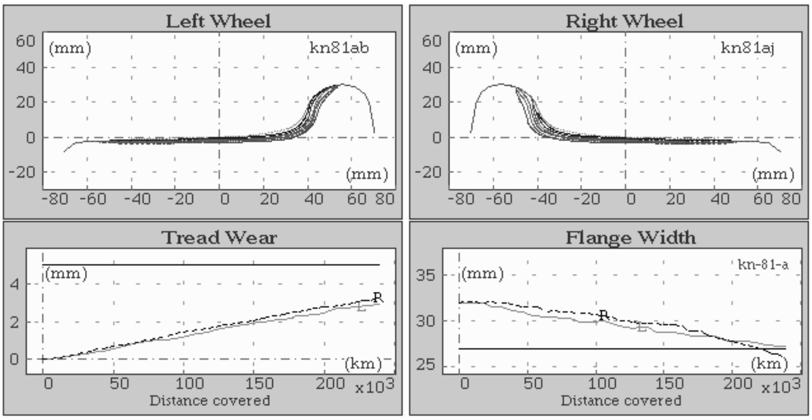


Fig. 10. Wheel wear process of a vehicle type 81, on the East – West line

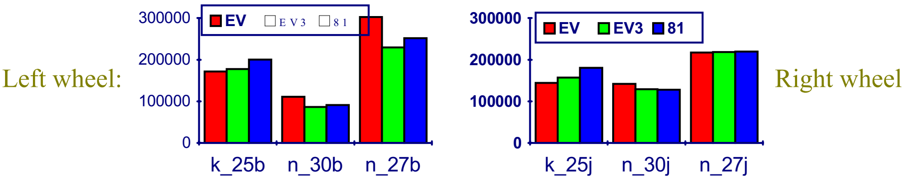


Fig. 11. Partial mileage performances, East – West line

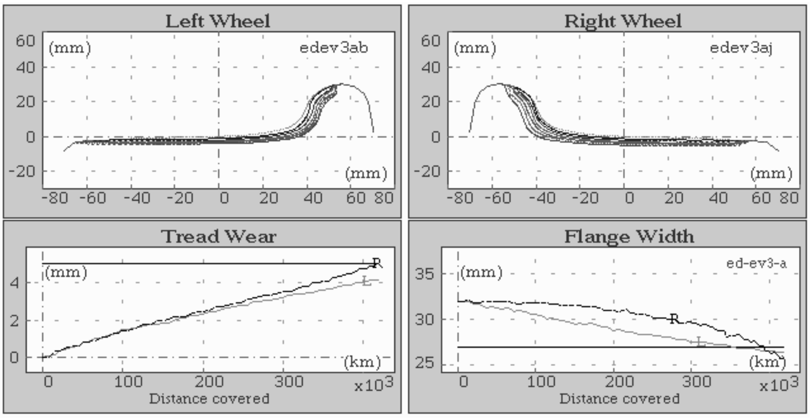


Fig. 12. Wheel wear process of a vehicle type EV3, on the North – South line

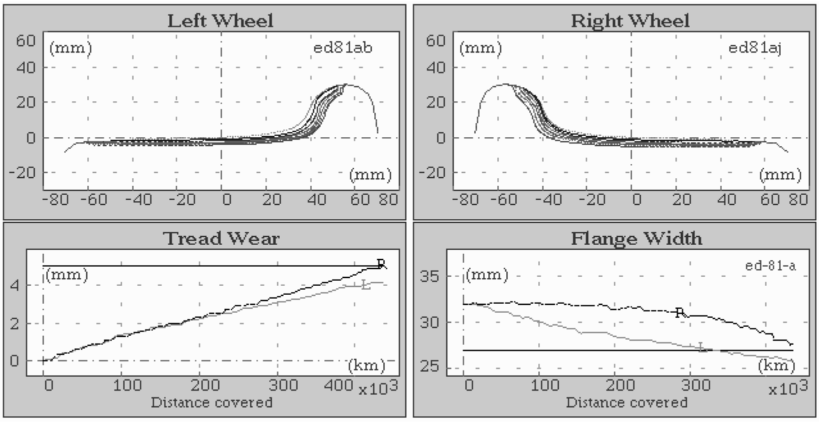


Fig. 13. Wheel wear process of a vehicle type 81, on the North – South line

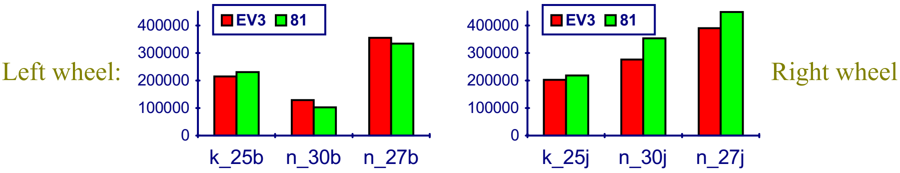


Fig. 14. Partial mileage performances, North – South line

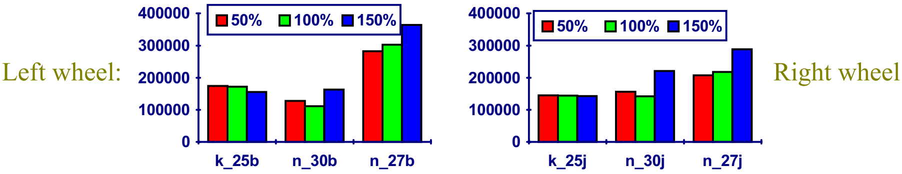


Fig. 15. Partial mileage performance (km) vs. longitudinal stiffness-version diagrams on the East – West metro line, Vehicle type EV

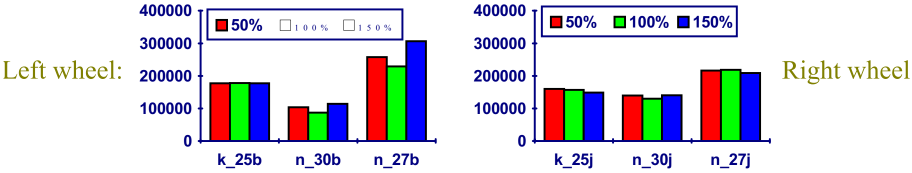


Fig. 16. Partial mileage performance (km) vs. longitudinal stiffness-version diagrams on the East – West metro line, Vehicle type EV3

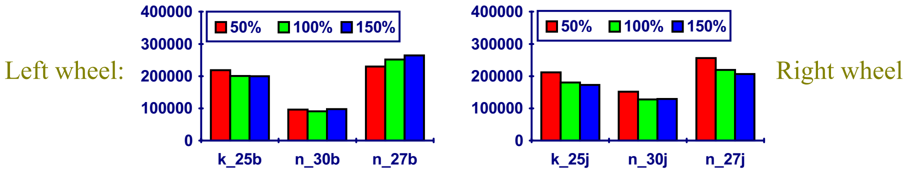


Fig. 17. Partial mileage performance (km) vs. longitudinal stiffness-version diagrams on the East – West metro line, Vehicle type 81

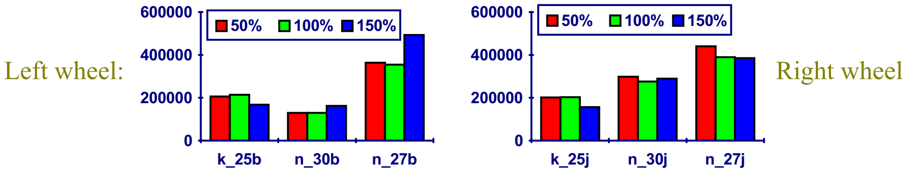


Fig. 18. Partial mileage performance (km) vs. longitudinal stiffness-version diagrams on the North – South metro line, Vehicle type EV3

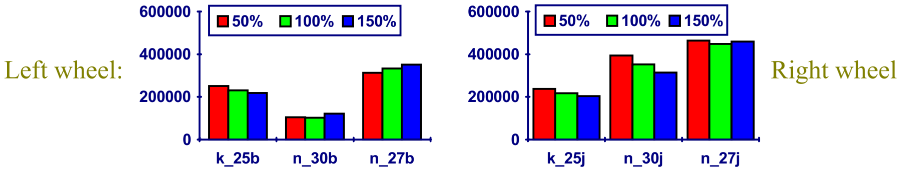


Fig. 19. Partial mileage performance (km) vs. longitudinal stiffness-version diagrams on the North – South metro line, Vehicle type 81

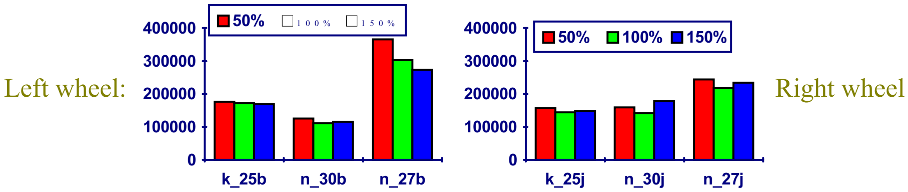


Fig. 20. Partial mileage performance (km) vs. lateral stiffness-version diagrams on the East – West metro line, Vehicle type EV

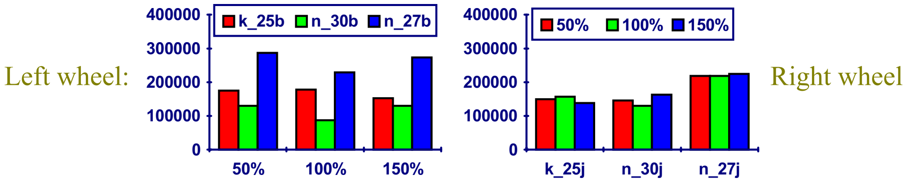


Fig. 21. Partial mileage performance (km) vs. lateral stiffness-version diagrams on the East – West metro line, Vehicle type EV3

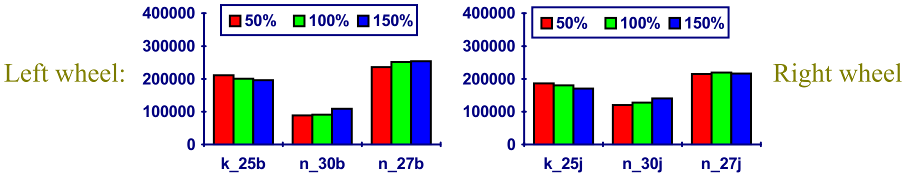


Fig. 22. Partial mileage performance (km) vs. lateral stiffness-version diagrams on the East – West metro line, Vehicle type 81

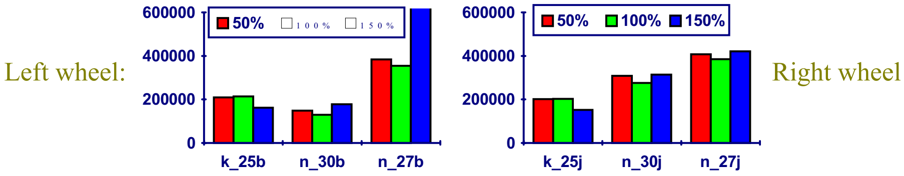


Fig. 23. Partial mileage performance (km) vs. lateral stiffness-version diagrams on the North – South metro line, Vehicle type EV3

The results of the computations are shown in *Figs.* 25–29.

The application of the initial wheel profile type K6 results in greater potential lateral displacement of the wheelsets, so in this case a decreasing wear tendency appears booth on the flange and on the tread. The wear decrease is more intensive on the North – South metro line, where the construction track gauge was initially reduced to 1432 mm.

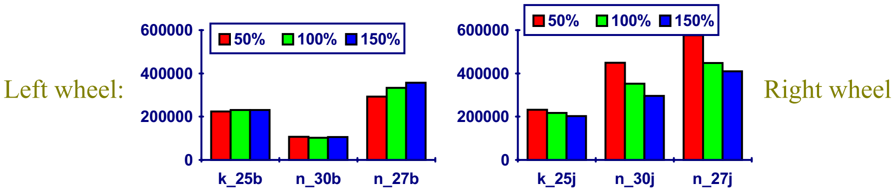


Fig. 24. Partial mileage performance (km) vs. lateral stiffness-version diagrams on the North – South metro line, Vehicle type 81

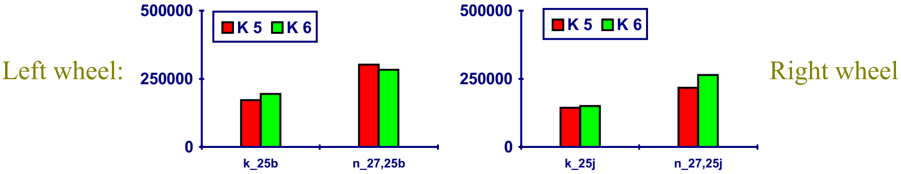


Fig. 25. Partial mileage performance (km) vs. initial wheel profile version diagrams on the East – West metro line, Vehicle type EV

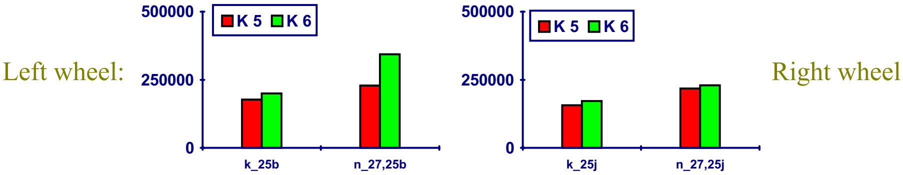


Fig. 26. Partial mileage performance (km) vs. initial wheel profile version diagrams on the East – West metro line, Vehicle type EV3

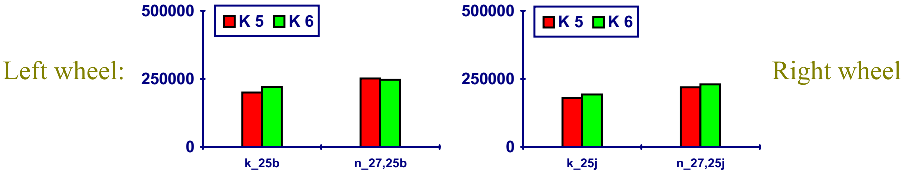


Fig. 27. Partial mileage performance (km) vs. initial wheel profile version diagrams on the East – West metro line, Vehicle type 81

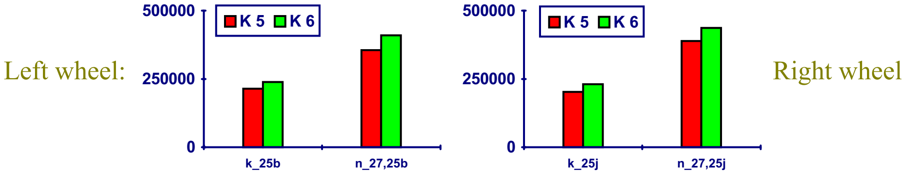


Fig. 28. Partial mileage performance (km) vs. initial wheel profile version diagrams on the North – South metro line, Vehicle type EV3

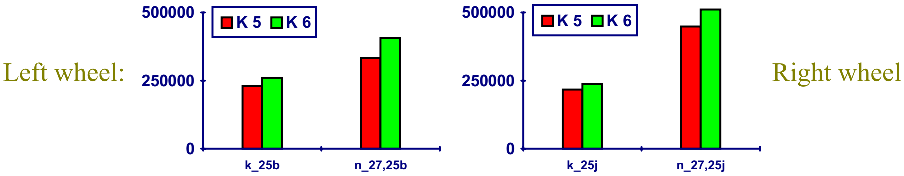


Fig. 29. Partial mileage performance (km) vs. initial wheel profile version diagrams on the North – South metro line, Vehicle type 81

6. Conclusions

On the basis of the simulation results some conclusions can be drawn and some recommendations can be given concerning feasible methods to increase the mileage performance, i.e. the total distance covered by the metro trains between two wheel profile renewals by turning on the lathe.

- Concerning the wheel profile wear phenomenon, it is characteristic in the operation of all the three types of vehicles of the Budapest metro system that the exhaustion of the permitted wheel profile dimensions occurs always with the excessive decrease in the flange widths.
- Comparing the wheel profile wear conditions in the operation on the North – South and East – West Budapest metro lines they are considerably different due to the significantly different curvature distributions along the tracks.
- On the basis of the results of wear simulations in the framework of sensitivity analysis a comparative study was carried out to select more advantageous metro vehicle running gear parameters that can ensure higher mileage performance values.
- The deviation in the total distance covered up to achieving a prescribed wheel tread and flange wear at the right and left wheels is generally between 5 and 10%.

- It was experienced that a 50% decrease in longitudinal axlebox guidance stiffness led to an increase of about 8% in mileage performance on both metro lines, in accordance with the expectations.
- A similarly advantageous effect was experienced concerning the increase of the lateral axlebox guidance stiffnesses, namely an increase of 50% in lateral stiffness led to an increase of about 15% in mileage performance, especially on the East – West line rich in curved sections.
- The advantageous increase in mileage performance (about 5%) in case of initial profiles K6 in comparison with the mileage performances achieved by using profiles K5 was significantly experienced in almost all cases, but on the North – South line, the increase in mileage performance was definitely greater (about 10%) with high certainty due to the reduced (1432 mm) constructional track gauge.

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