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ON DETERMINISTIC AND STOCHASTIC SIMULATION OF WHEEL AND RAIL PROFILE WEAR PROCESS[1]

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Abstract

In the paper the formerly elaborated simulation method for determining the wear propagation on the wheel-tread and flange is extended for the case of combined wheel/rail wear processes. In the simulation method the straight and curved track sections are treated distinctly taken into consideration a non-linear vehicle model moving on the track sections belonging to a specified network. The material removal is considered to be proportional to the dissipated energy and the specific normal traction distribution on the actual common contact patches. Also the frequency of contact is involved into the analysis characterising actual railway operation. As a result of the simulation procedure both the magnitude of the rail wear and its distribution along the track (right and left rail distinctly), as well as the wheel wear (right and left wheels distinctly) can be determined for the considered railway system. In the analysis also the stochastic lateral rail irregularities are taken into consideration. It will be shown how it is possible to extend the combined wheel/rail simulation procedure for the case of semi-Markovian stochastic operation conditions of the vehicles on a topologically specified railway network.

Keywords: vehicle–track dynamics, combined wheel and rail wear simulation.

1. Introduction

In the combined rail/wheel wear simulation method the straight and curved track sections are treated distinctly. The material removal is considered to be proportional to the energy dissipated on the actual common contact patches of the rail and wheel. As an important parameter, also the contact frequency is involved into the numerical analysis of the railway operation process considered. As a result of the simulation procedure both the magnitude of the rail profile wear for the track sections of different curvature, (right rail and left rail distinctly), and the wheel wear (right wheels and left wheels distinctly) can be determined for the railway operation process

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considered. In the analysis also the stochastic lateral rail irregularities are taken into consideration based on the spectral density functions evaluated from track misalignment and gauge measurements.

2. Dynamical Model

The lumped-parameter track–vehicle model consists of the vehicle body, the bogies, the wheel-sets and the discrete masses representing the track inertia. The sprung structural connections between the rigid bodies mentioned are modelled by piece-wise linear characteristics, while the dampers supposed to be parallel to the former ones are definitely linear (see *Fig. 1*). The used wheel and rail profiles can be practically arbitrary.

The track can be composed of specified straight and curved sections coming one after another in an arbitrary order. The transition curves of arbitrarily prescribed curvature functions can be included between the straight and circular sections.

- The track can be laterally 'imperfect', i.e. a stochastic lateral irregularity can be taken into consideration.
- The vertical wheel loads are constants on the straight sections, while in curved sections the quasi-static compensation of the centrifugal forces and the super-elevation are carried out.

- The wheel–rail contact on the wheel tread is treated as a creep-dependent force transfer spot, the creep coefficients are treated by Kalker's linear theory.
- The longitudinal and lateral contact forces, as well as the spin moment are bounded by the values based on a constant sliding friction coefficient.
- The flanging is considered as a conditional, laterally elastic and damped linear connection between the wheel-set and the mass representing the rail inertia.
- In the model, a specified constant torque is acting on each wheel-set, which represents the resultant traction resistances and the eventually acting tractive or braking torques.
- It is always assumed that no braking torque is exerted by frictional tread braking.

The vehicle–track model in question takes into consideration track section-wise constant travelling velocities and torques on each wheel-set. It is reasonable to use a constant average travelling velocity along the whole railway line examined, and also an average torque to act on the wheel-sets on the basis of a preliminary 'speed – distance covered' analysis.

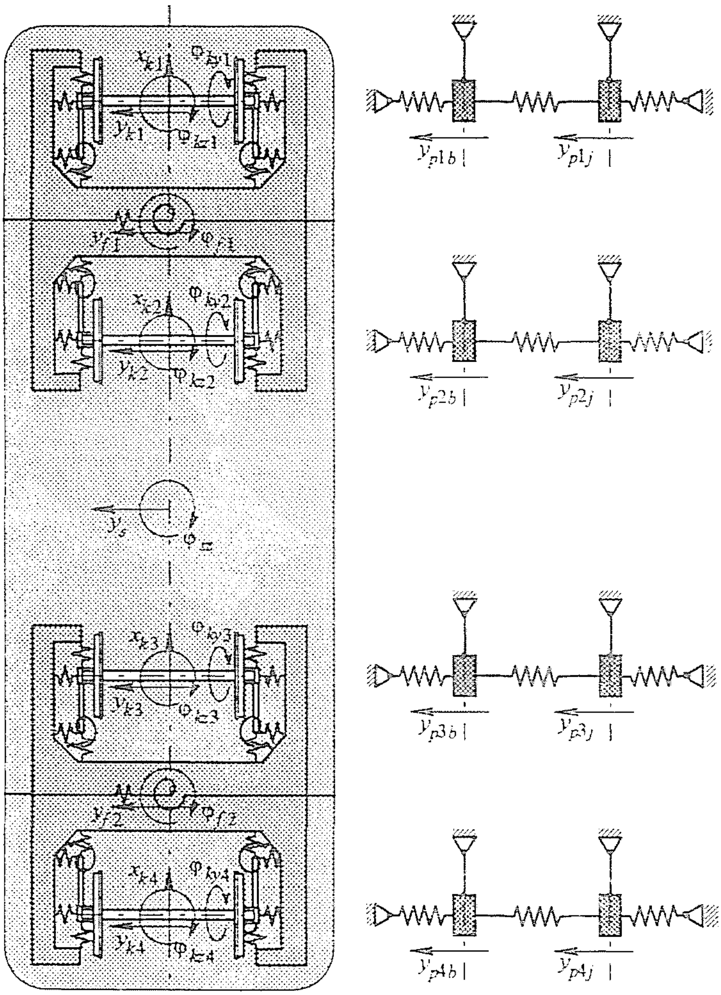

Fig. 1. Dynamical model of the vehicle–track system

3. Wear Hypothesis

The most frequently used wear hypothesis was formulated in terms of the proportionality between the specific energy dissipated over the contact surface and the specific mass removal for the unit of the distance covered [3].

Formula

$$\frac{\partial m}{\partial s} = k_t \left(F_x \nu_x + F_y \nu_y + M_s \nu_\omega \right)$$

is valid for the rolling contact of the wheel and the rail realized on the wheel tread, while for the sliding contact of the flange and the rail head formula

$$\frac{\partial m}{\partial s} = k_f F_f \frac{\Delta \nu_s}{v}$$

is valid. Coefficients k_t and k_f can take different values for the wheel and rail materials, which fact should be taken into consideration in the simulation procedure. In the present paper coefficients kt and kf are considered as known constants. Nevertheless the latest results of measurements show that the coefficients in question can depend on the total distance covered by the vehicle [6].

It is to be mentioned that the material removal in every discrete step of simulation based on formula

$$\Delta m = \frac{\partial m}{\partial s} \Delta s$$

is distributed among the profile partition elements covered by the contact patch. The principle of the distribution mentioned is based on the weighting factors reflecting the relative portion of normal force acting on the partition elements, i.e. for the i-th partition element intersecting the contact patch normal force F_i is to be divided by total normal force $F = \sum F_i$ acting on the whole contact patch. It can be seen that the material removal is carried out by combining the dissipated energy based wear hypothesis and the wear hypothesis based on the normal force of contact [1].

4. Model of Operation

It is obvious that the intensity of wear of surfaces undergoing rolling contact is proportional to the frequency of contact. This fact emphasises that the intensity of wheel wear is proportional to the distance covered by the wheel, while the intensity of rail wear is proportional to the number of wheel-sets passed through the track cross section considered. In the real railway operation many kinds of vehicles should be reckoned with. In accordance with our wear simulation procedure vehicles of different geometrical and mechanical parameters can be considered and after a sequential computation of rail wear conditions the expected rail wear propagation can be determined by weighted averaging of the results of the individual computations. In each computation step a specified number of axle passages should be taken into consideration.

5. Simulation of Worn Profiles

The fundamental idea of the wear simulation is to consider the actual wheel profile and railhead profile as the basis of the contact geometrical, dynamical and energetical (dissipation) operations. The energetical operations result in the wear load distributions along the wheel meridian profile and the railhead profile. The 'stabilized' wear-load distribution both for the wheel profile and the rail profile is determined on the basis of a sufficiently long distance covered on straight or curved track sections. The discretization principle applied in the simulation procedure implies the extension of the validity of the wear load distributions mentioned above. In case of wheel wear simulation the stabilized wear load distribution is considered as valid for an extended (≈ 1000 km) distance covered. In case of rail wear simulation the stabilized wear load distribution with respect to the passage of a single wheel-set is considered as valid for the passages many ($\approx 40\,000$) wheel-sets.

The profile alteration, i.e. the reduction in rolling radii and reduction in railhead height ordinates is carried out by using the wear load distributions mentioned above and appropriate physical and mathematical smoothing procedures to balance the errors caused by the used discretization method. In this way, a discrete step of profile alteration due to wear is done both for the wheel and the rail examined. The resulting new wheel and rail profiles take over the role of the initial profiles, and a subsequent discrete step can be done, etc. In the course of the whole simulation the mentioned smoothing procedures should be sequentially applied. The physical smoothing procedure is built up on the basis of continuous evaluation of the geometrical compatibility of the contacting rail and wheel profiles. The mathematical smoothing is based on the C_1 spline method, i.e. a smoothly connected piece-wise second order parabola system is used.

The described simulation method results in the worn wheel and rail profile sequences reflecting the combined wear propagation process under the considered operation conditions.

6. Simulation Results

The simulation procedure was carried out by using real vehicle and track data. The considered vehicle was a four-axle rapid train carriage of traditional construction, see *Fig. 2*.

The considered track was the southern ramp of the 'Gotthard Line' between Airolo and Bodio. The top view of the line topology is visualized in *Fig. 3*. The distribution of the evaluated track curvatures can be seen in *Fig. 4*.

With the simulation some special conditions were chosen to represent the wear propagation process in question. The computation results are shown in *Figs. 5–10*.

In *Fig. 5* the wear propagation on the left and right wheels can be seen up to mileage performance 21800 km. In the course of the simulation the mass removal from the wheels was carried out after each 872 km distance

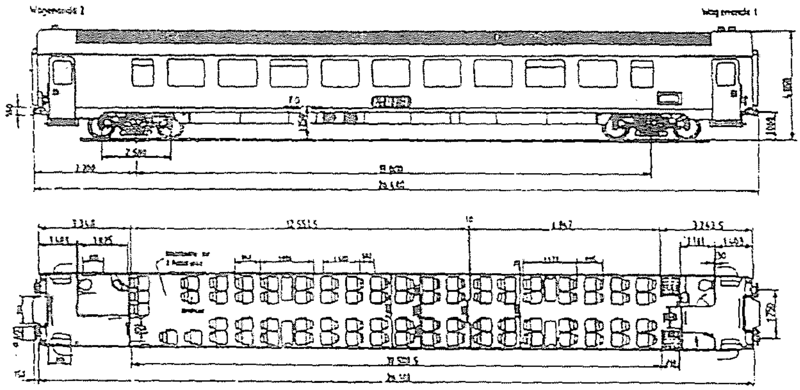

Fig. 2. Passenger carriage for rapid train operation

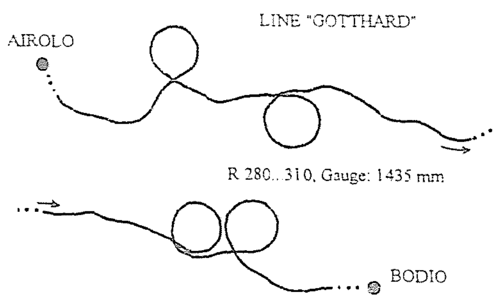

Fig. 3. The considered railway line: The southern ramp of 'Gotthard line' between Airolo and Bodio

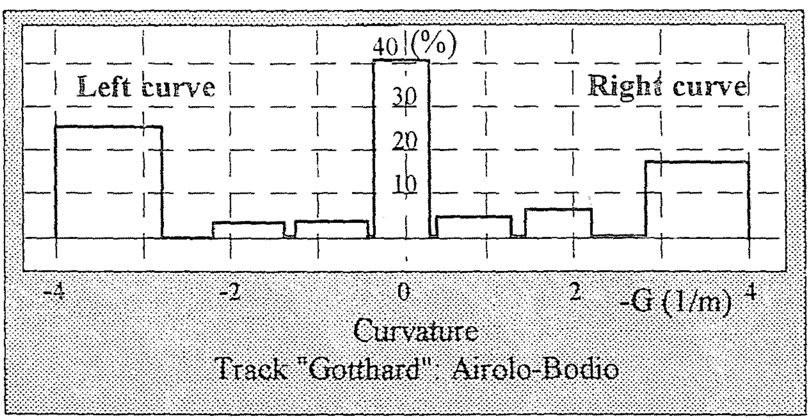

Fig. 4. Distribution of curvatures

covered. The worn profiles indicated in *Fig. 5* represent profile states in steps of 4360 km.

In *Figs. 6–10* the wear propagation and wear load distributions diagrams are plotted for the left and right rail heads. The total number of axle passages were of 10^6 order of magnitude.

The above mentioned characteristic diagrams can be seen for the straight sections in *Fig. 6*, for the curved sections of radius +1400 m in *Fig. 7*, for the curved sections of radius −1400 m in *Fig. 8*, for the curved sections of radius +500 m in *Fig. 9* and for the curved sections of radius −500 m in *Fig. 10*. The positive signs identify the left curves while the negative signs identify the right curves.

7. Stochasticity of Wear Propagation of the Wheel and Rail Profiles

The simulation procedure should be modified if the non-conform character of the wheel profiles is taken into consideration. On the railway line under consideration several types of railway vehicles are in operation and each vehicle has its own wheel profiles in a certain state of wear.

Due to the mentioned fact the material removal should be carried out by using a modified weighting of the wear-load functions in accordance with the actual statistical manifold of the wheel profiles passing through the track cross section selected for examination. In formulae:

$$w_i = \sum_{j=1}^{n_{vp}} w_{ij} p_j, \qquad \sum_{j=1}^{n_{vp}} p_j = 1, \qquad i = 1, 2, \ldots, N,$$

where w_{ij} is the conditional wear load on the rail profile in the i-th profile partition element caused by the j-th class of wheel profiles passing through the track cross section considered, p_j is the probability of the passage of a wheel profile belonging to the j-th class, while N is the number of partition elements on the rail head.

With the knowledge of wear load distributions w_i $i = 1, 2, \ldots, N$ the rail profile of the track cross section can be modified as it has been introduced for the deterministic case [7].

There are four possible operational cases to be distinguished with the rail wear profile process:

a.) The wheel profile manifold and the probability distribution of the profile classes are stabilized (many vehicles, methodical profile renewal).

b.) The wheel profile manifold changes, the probability distribution is stationary (few vehicles, rigid operation scheduling).

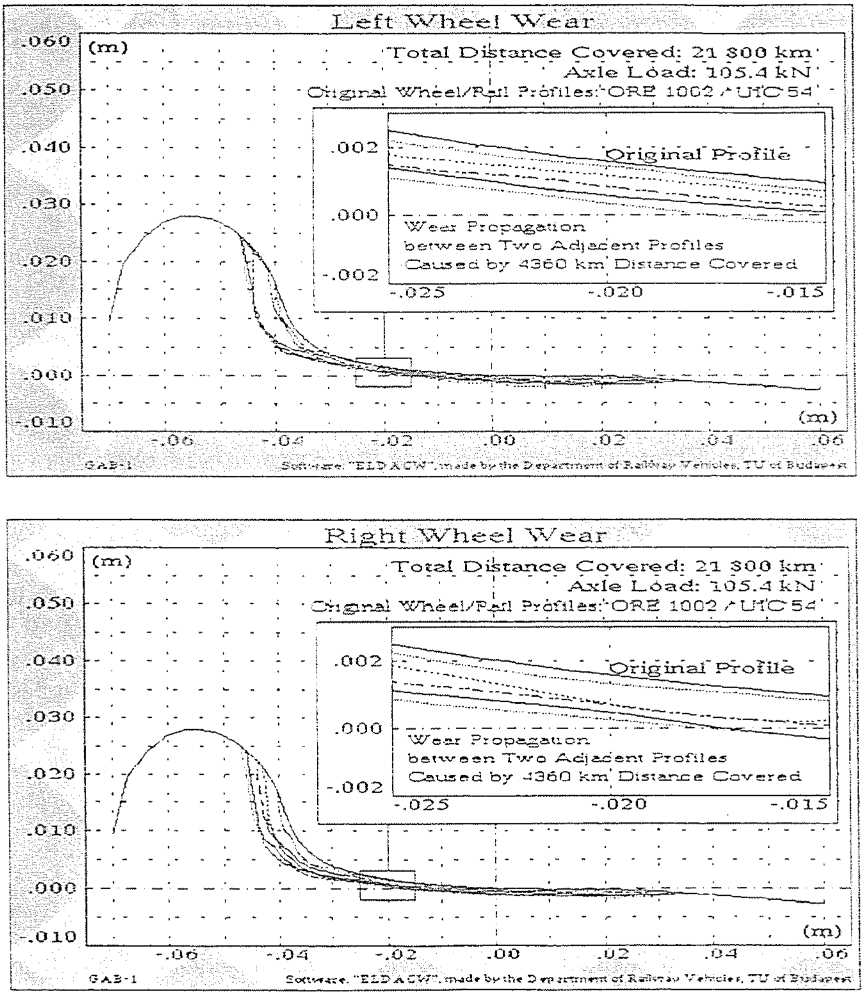

Fig. 5. Wheel profile wear propagation

c.) The probability distributions change, the profile manifold is stationary (many vehicles in operation on an extended network, fluctuating operation conditions on the line considered).

d.) Both the profile manifold and its probability distribution change (few vehicles in operation on a small network, fluctuating operation conditions on the line considered).

The simulation procedure formulated for a single railway line can be extended for a complete railway network [4],[5]. The stochastic operation conditions of the trains along the branches of the graph representing the network in question can be treated in the framework of semi-Markovian

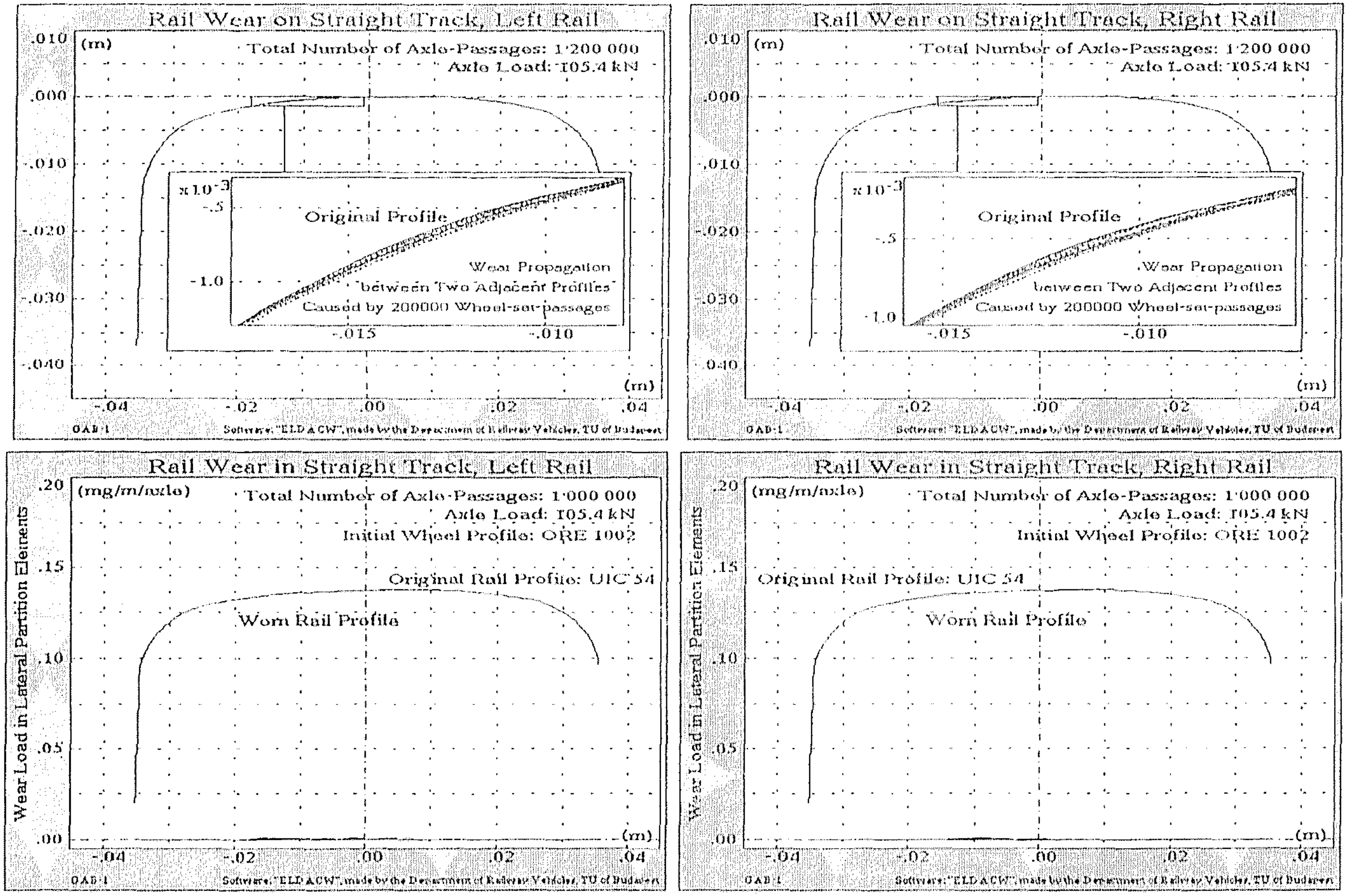

Fig. 6. Rail profile wear propagation in straight track

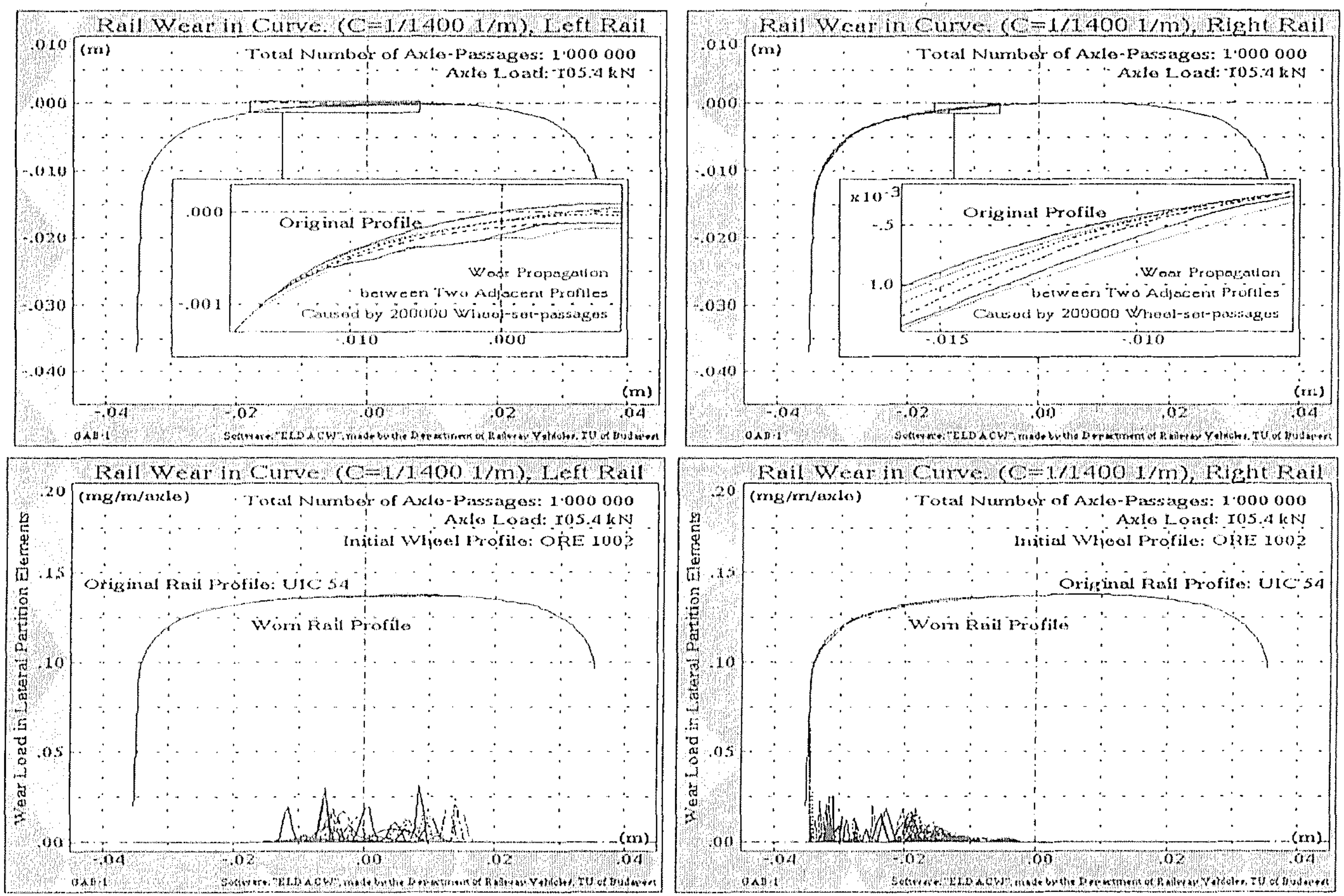

Fig. 7. Rail profile wear propagation in curved track of radius 1400 m

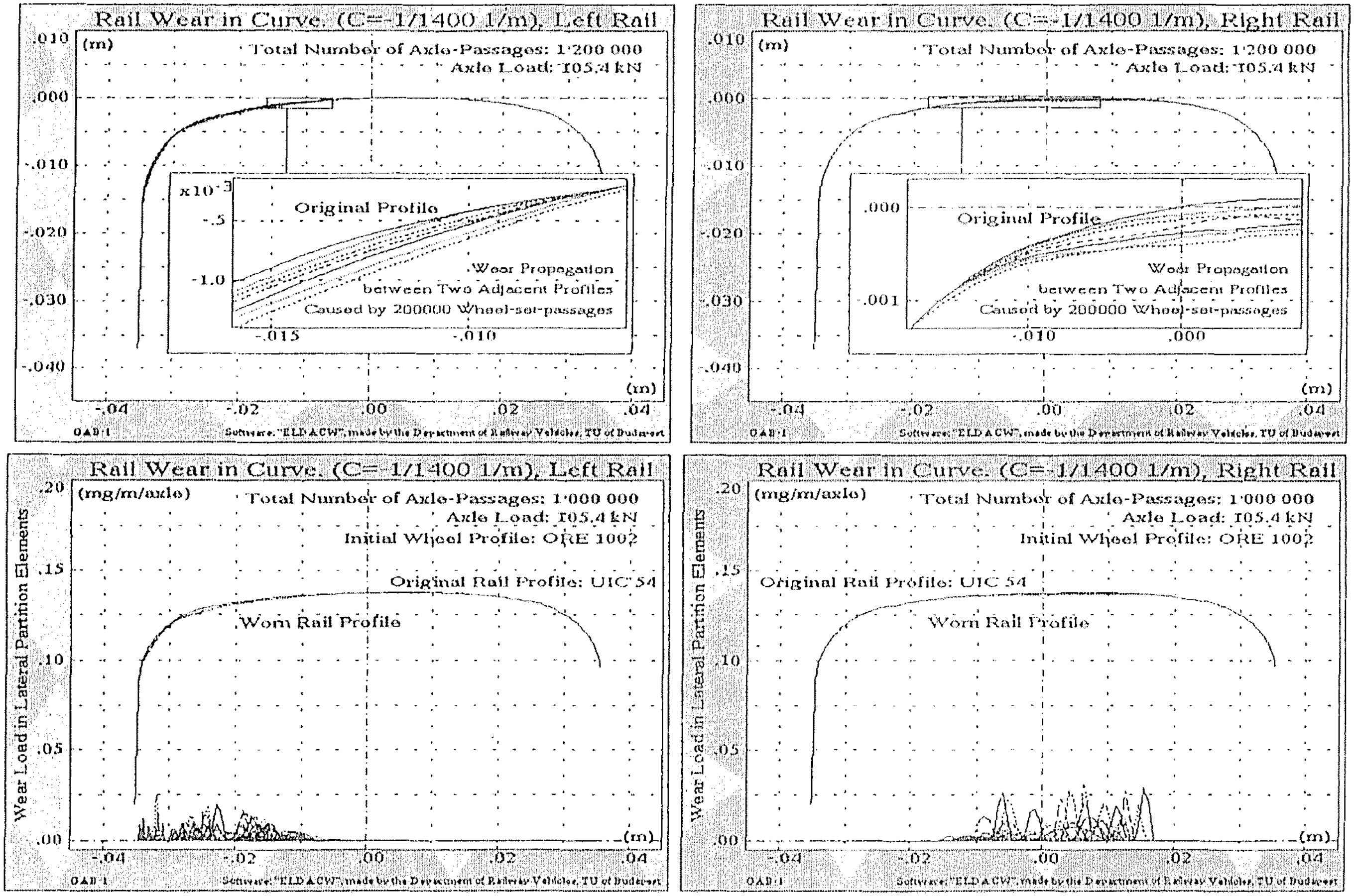

Fig. 8. Rail profile wear propagation in curved track of radius −1400 m

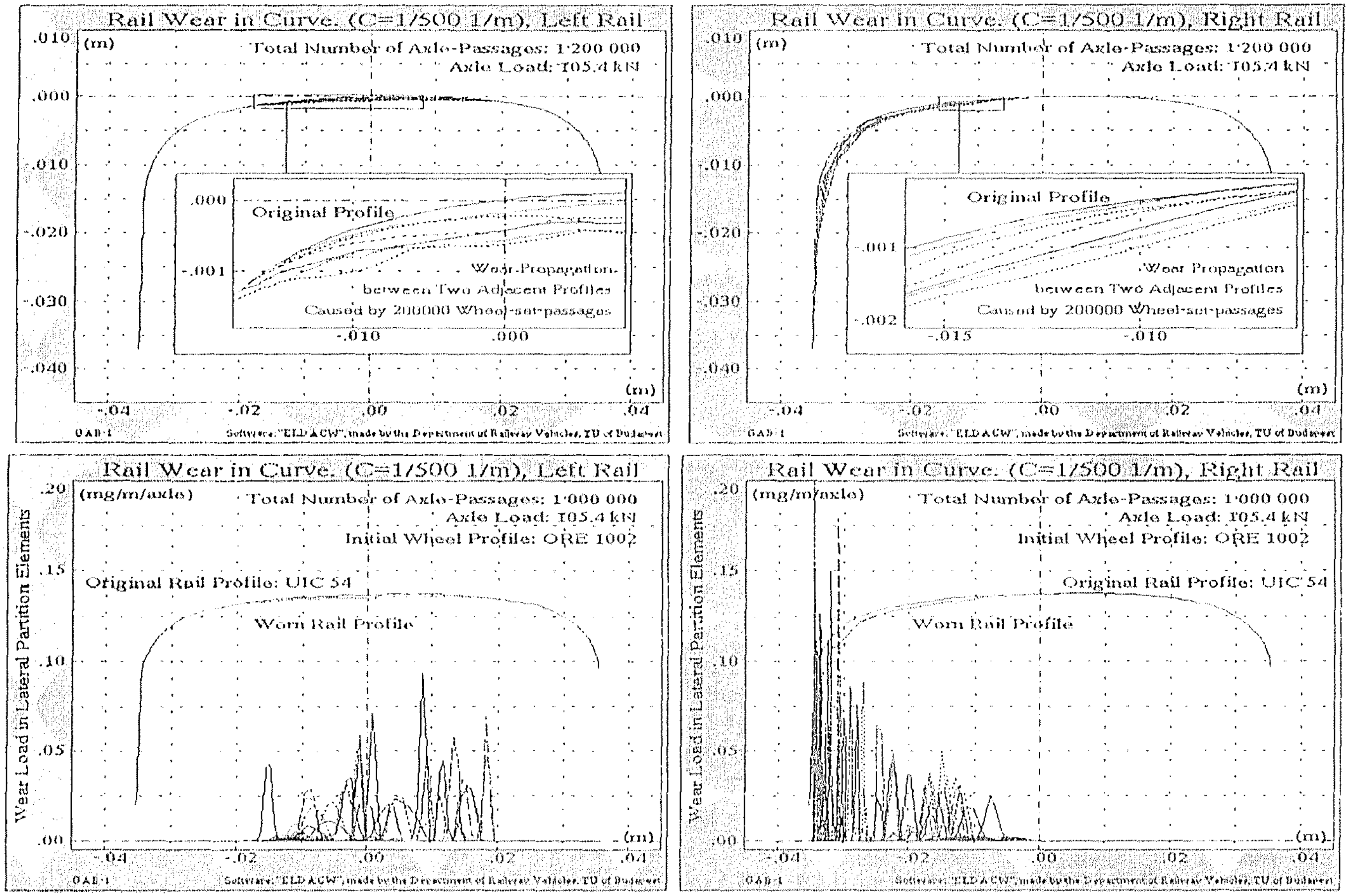

Fig. 9. Rail profile wear propagation in curved track of radius 500 m

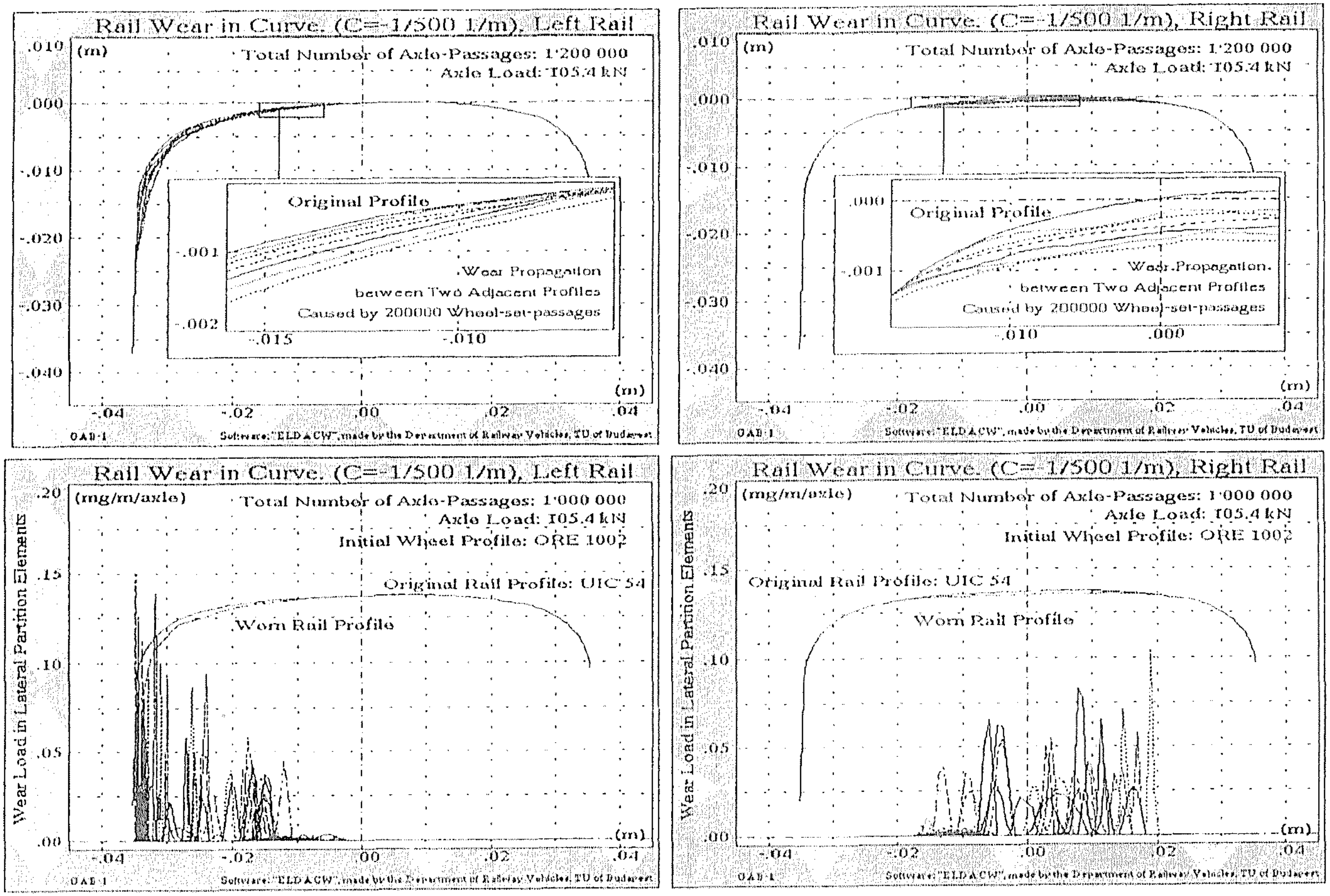

Fig. 10. Rail profile wear propagation in curved track of radius –500 m

model based on the transition probability matrix and the matrix of the conditional probability distribution functions characterizing the probability measure of the number of passages on the lines in the examined network.

Though the stochasticity of the wheel and rail wear process has appeared due to the presence of stochastic track irregularities representing excitation sources for the lateral motion process of the vehicle moving along the track and the material removal due to wear takes over this stochasticity, the essential stochastic character of the combined wheel and rail wear process is caused by the stochasticity of the operational process. In former papers [4],[5] the tools of simulation have been elaborated in the framework of the mentioned semi-Markovian model.

The stochastic simulation of the wheel and rail wear processes lead to the realisation functions of the wheel and rail profiles in a natural way. The sequential repetition of the simulation of the motion and wheel and rail profile wear processes the realisation manifold consisting of the worn profiles can be determined. These two profile manifolds are the representations of the two characteristic stochastic wear processes, describing the wheel and rail profile alteration in the course of operation. The parameter space of the stochastic processes in question is the lateral position co-ordinate. The marginal distributions and the statistical parameters (expectation, variance etc.) can be determined to each lateral position. With knowledge of the mentioned statistical quantities a very impressive, detailed wear characterisation can be carried out. For the case of the wheel profile wear the diagrams in [5] can be referred to.

8. Concluding Remarks

- The dynamics and tribology based simulation model is apt to give predictions about the wheel and rail wear propagation caused by the regular operation of specified vehicles on a specified line.
- In the simulation model disctretization technique is used. To achieve reasonable accuracy and computation time consumption the selection of the discretized lengths of distance covered and the number of axle passages in a discrete computation step are of basic importance.
- The simulation model was tested by using the data of the 'Gotthard' line and a rapid train carriage. The computation results show that the wear load of the rail head on straight track sections is negligible in comparison with those realized in curved sections of 1400, 500 and 300 m radii.
- The wear coefficients belonging to the rail should be determined on the basis of extended rail profile measurements reflecting the variation with time of the profiles under known loading conditions, i.e. by taking into account the axle loads and the total number of axle passages.

- The combined wheel and rail profile wear simulation can be extended to the case of taking into account specified statistical wheel profile and rail profile manifolds. In this case the whole combined wear process becomes a stochastic phenomenon.
- Taking into consideration the parameter spectrum of the vehicles and the random character of the railway operation on a network the expected wheel and rail wear propagation can also be predicted.
- The latter predictions can be the basis of a computer based complex rail and wheel management system to be elaborated in the future.

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