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FEM BASED PARAMETRIC DESIGN STUDY OF THE TIRE PROFILE USING DEDICATED CAD MODEL AND TRANSLATION CODE

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Abstract. *In this paper a finite element method (FEM) based parametric design study of the tire profile shape and belt width is presented. One of the main obstacles that similar studies have faced is how to change the finite element mesh after a modification of the tire geometry is performed. In order to overcome this problem, a new approach is proposed. It implies automatic update of the finite elements mesh, which follows the change of geometric design parameters on a dedicated CAD model. The mesh update is facilitated by an originally developed mapping and translation code. In this way, the performance of a large number of geometrically different tire design variations may be analyzed in a very short time. Although a pilot one, the presented study has also led to the improvement of the existing tire design.*

Key Words: *Tire, Parametric Design Study, Steady-state Rolling, FEM, FEA*

1. INTRODUCTION

The tire plays an important role in vehicle behavior and traffic safety in general. It is also a very challenging structure regarding its design, due to its complexity, specific materials and adverse conditions of exploitation. The tire design process is still mostly based on tacit knowledge and experience of the designer, so it assumes that the final design contains features of a rather arbitrary nature. Constant efforts are taken to improve and shorten this process by application of the latest CAD/CAM/CAE technologies.

The tire design process consists of several main phases [1], which may be summarized as: identification of goals/requirements, selection of design features and verification of performance. The first phase implies setting up of performance targets; it is very much determined by tire purpose, customer expectations, manufacturing requirements and governing standards. These requirements also dictate the choice of primary design parameters like

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tire diameter, tire width or section height. The second phase includes the tire profile shape design (mold contour) and its structural components, the design of tread pattern and the choice of tire materials. A large number of secondary design parameters may be varied in this phase, and although their influence on the tire performance is generally known, the sum effect and intensity of mutual parameter changes is hard to predict. The performance of tires is verified through a series of criteria, mainly related to different types of tests, which they undergo in the laboratory or outdoor conditions [1]. If only the physical prototypes were used for performance verification, the tire design process would become lengthy and expensive. For all above reasons, the computer based simulations of tire behavior, mostly based on the finite element method (FEM), have become a standard part of the tire design process.

Verification of the most important aspects of the tire performance may successfully be conducted using a combination of the static finite element analysis (FEA) and the steady-state rolling (SSR) FEA based on the mixed Eularian/Lagrangian approach, which, as shown by Koishi and Kabe [2], represents an optimal approach to simulation of the rolling tire behavior. This statement also relies on the fact that the steady-state rolling represents the primary operational mode of the tire since the transient states in the tire service tend to be of a relatively short duration comparing to the steady-state rolling states [3].

The FEM based parametric design studies of the tire design available in the literature [4,5,6] mainly investigate the impact of changes in structural parameters such as tire materials, the number of belts, the density of cords and the like on tire behavior in service. In all those studies, the parameters are chosen in such a way that they may easily be modified by a simple change of certain numerical values within the finite element (FE) model. None of those modifications causes the shape of the finite element mesh to change because the geometric features those parameters relate to are approximated by section or material properties, associated to corresponding finite elements. For example, not every wire in belts or carcass is modeled separately; rather, they are represented by continuous media which has the density that is controlled by that of the cords (number of wires per unit length) and input as a numerical value. The approach presented in this paper offers greater flexibility. It relies on a specially designed CAD model, which contains the geometric entities that facilitate the creation of the finite element mesh, and it, therefore, allows for a simple change of the structural parameters that are geometric by nature. The propagation of changes from CAD model to FE mesh is done automatically, thanks to the originally developed mapping and translation code. An algorithm has also been defined according to which, using the finite element model, optimization of the tire performance, i.e. parametric studies that investigate the impact of changes in geometry and material parameters on the tire behavior are performed [7]. Its use is demonstrated here through a pilot parametric design study of the tire profile shape and belt width, which shows the advantages and benefits of the proposed approach.

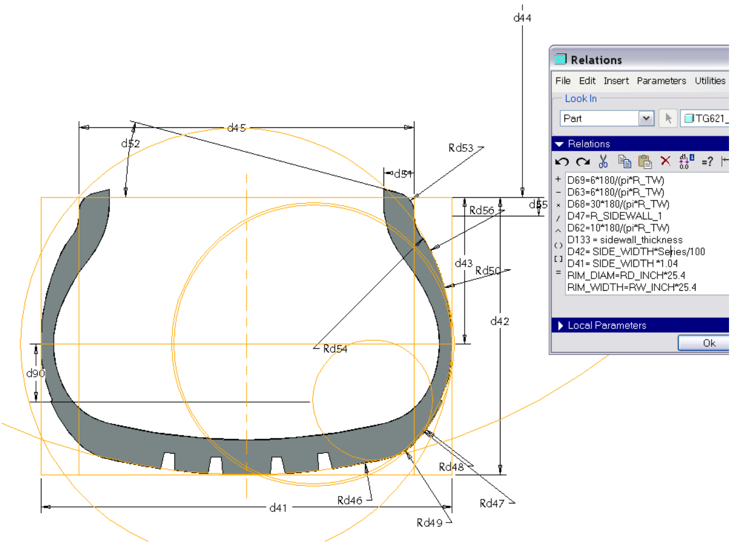
The dedicated CAD model described in this paper can also be used within single- and multi-objective design optimization studies [8, 9]. It this case it would bring even greater benefits as the number of FE model instances that have to be created during such studies typically gets very large.

2. CAD BASED FE TIRE MODELS

To perform the FEA of tires, FE models of different complexity are used. The most common ones are FE tire models without detailed tread (with circular channels only) [3-7, 10] and FE models with detailed tread [10-13]. Before this study was performed, the response of FE models with and without detailed tread to application of vertical load as well as to braking, accelerating and cornering, had been compared in order to decide which of the two should be used within the study [10]. The comparison showed that although the contact pressure distribution at the tire footprint is locally different, the tire forces and moments obtained using the two models did not differ significantly. One could therefore conclude that it was, in most cases, sufficient to use the FE model without detailed tread to simulate the operational behavior of the tire. Thus, such a model was as well chosen for this study.

2.1. CAD model

The geometry of CAD model is constructed in a manner that is very familiar to tire designers, i.e. its construction circles and curves are based on the traditional way the tire profile is designed (Fig. 1). Such an approach enables them to familiarize with the model and easily make design changes, without thorough knowledge of the CAD system itself. When the model is built, one of the main goals is to separate the influence of important tire parameters on tire shape. Thus, for example, the width of the crown area may be controlled separately from the belt width.



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D69=6*180/(pi*R_TW)
D63=6*180/(pi*R_TW)
D68=30*180/(pi*R_TW)
D47=R_SIDEWALL_1
D62=10*180/(pi*R_TW)
D133 = sidewall_thickness
D42= SIDE_WIDTH*Series/100
D41= SIDE_WIDTH *1.04
RIM_DIAM=RD_INCH*25.4
RIM_WIDTH=RW_INCH*25.4
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Fig. 1 2D CAD tire model with some of the construction circles and curves shown

CAD model is divided into zones that correspond to twelve structural components of the tire, which have associated parameters that may be changed independently of profile shape. Apart from basic geometric forms, the CAD model contains geometric elements (points and lines/curves) that serve as the basis for the finite element mesh creation and automatically adapt to the changes in the tire geometry [6].

The 2D CAD model described here is based on 3D CAD model developed earlier, as presented by Stojković et al. [14,15], with which it may be combined in cases when the tire tread is going to be modeled in detail. This 3D model has already been used as the base for various CAD/CAM/CAE applications [16,17].

2.2. Translation

A methodology for automatic update of the finite element mesh has been designed and implemented, which enables the mesh to adapt to the changes of geometric parameters of the CAD model. At first, an axisymmetric FE model is constructed based on the CAD model. This is done only once for a certain type of tire, using surfaces and curves exported from the CAD model [7]. After the building of the FE model is finished, the mapping is performed between its nodes and the points of the CAD model, based on their current coordinates. The mapping, which implies that every point in the CAD model has a corresponding node in FE model, is saved and, embedded into the translation code. From that moment on, an easy and fast creation of FE models based on CAD models with modified tire parameters is enabled. For all tire types that have similar inner structure, the same FE model may be used.

2.3. FE models

FE models used in the parametric study are described in detail in paper by Korunović et al [7]. At first, the axisymmetric tire model is built, which may be used for analysis of the tire inflation process. After the initial analyses are conducted, the 3D FE model based on the axisymmetric one is built, which serves as the basis for all the analyses to follow. The algorithm that describes the whole process, including the sequence of analyses to be conducted, the results that may be obtained by those and the actions to take if they are satisfactory or unsatisfactory is also given by Korunović et al [7]. The 3D FE model is adjusted in order to simulate the cornering of a tire rolling on the drum and verified through comparison with experimental results obtained on the drum machine [18].

3. Parametric Design Study of Tire Profile

Simultaneous use of the dedicated CAD model and the FE tire model will be illustrated here through a pilot parametric design study, performed on a model of existing 165/70 R13 tire.

3.1. Chosen parameters and design variations

The study examines the impact of changes in sidewall radius and belt width on the tire performance. Three different numerical values are in turn assigned to each of the two chosen parameters. Sidewall radius, located close to the crown, is adjusted in order to obtain different variations of the tire profile shape (Fig. 2). The belt width is changed in increments of 10mm in order to get three variations: a narrow-belted, normal and wide-belted tire. The values of the parameters are given in Table 1.

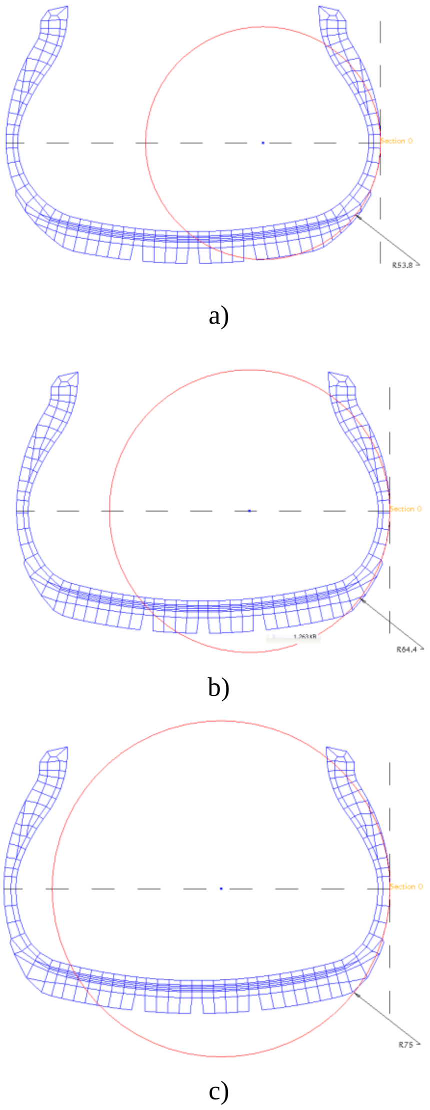


Fig. 2 Three tire instances obtained by changing the upper sidewall radius (R_1): a) R_1=53.8mm, b) R_1=64.4mm and c) R_1=75.0mm. The change affects the sharpness of shoulder area and the width of the crown (without affecting the belt width)

Table 1 Values of tire design parameters varied in the study

	Variation 1	Variation2	Variation3
Upper sidewall radius R_1 (mm)	53.8	64.4	75.0
Belt width (mm)	121.4	131.4	139.4

3.2. Types of FE analyses performed within the study

Each of the tire instances obtained by variation of the chosen parameters has been analyzed according to the proposed algorithm [7]. The results are compared in order to assess the influence of the parameter changes on stresses in the tire structure, contact pressure distribution and forces and moments generated on the footprint during inflation, application of vertical load, acceleration, braking and cornering on dry surface. In this pilot study, the arbitrary friction coefficient of 0.6 between the tire and the surface and tire velocity of 10km/h are chosen so as to minimize the time needed for the analyses to finish. A real-life study requires a more realistic description of friction and a range of velocities to be used, as shown in paper by Korunović et al [7].

3.2. Results

3.2.1. Inflation

FEA of tire inflation may be done on an axisymmetric or 3D tire model. The first one represents the logical choice, as FEA of the axisymmetric model needs much less time to finish. In Fig. 3 carcass stress, obtained as the result of axisymmetric analysis, is compared for three tire variations with different sidewall radii. Tire models are inflated to the pressure of 2 bar (0.2 N\mm^2). As the value of radius rises, the difference between the lowest and the highest value of carcass stress becomes larger. At point 2 a sudden drop of the stress is present, because the returning portion of carcass takes over a part of carcass load. Outwardly returning portion of the carcass is not taken into account.

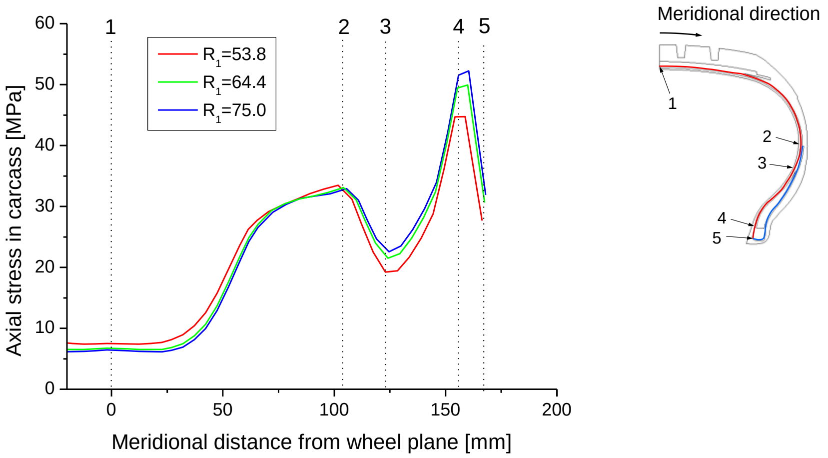


Fig. 3 Carcass stress comparison for tire variations that differ by value of R$_1$.
The characteristic points on carcass are: 1 – midpoint, 2 – point closest to the end of returning portion, 3 – point on the edge of filler, 4 – point on the upper edge or bead wire and 5 – point on the lower edge or bead wire

Difference in the carcass stress between three tire variations that have different belt width is less obvious and thus will not be shown. The stress in the crown area is very similar for all belt widths, while in the bead area it gets slightly higher for tire having wider belts and lower for tire having narrower ones.

3.2.2 Static FEA of vertically loaded tire

Load-deflection curve and footprint stress distribution are the most common types of results that tire designer wants to obtain from FEA of a vertically loaded tire. The study shows that the sidewall radius variation does not affect the load-deflection curve in a noticeable way, while the widening of the belts makes the tire noticeably stiffer (Fig. 4).

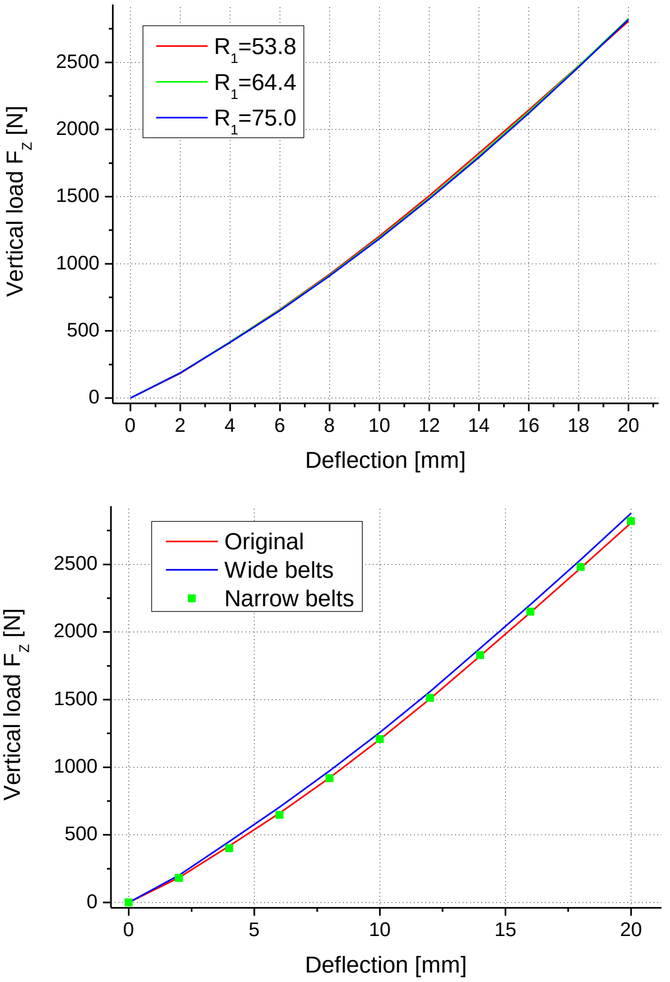
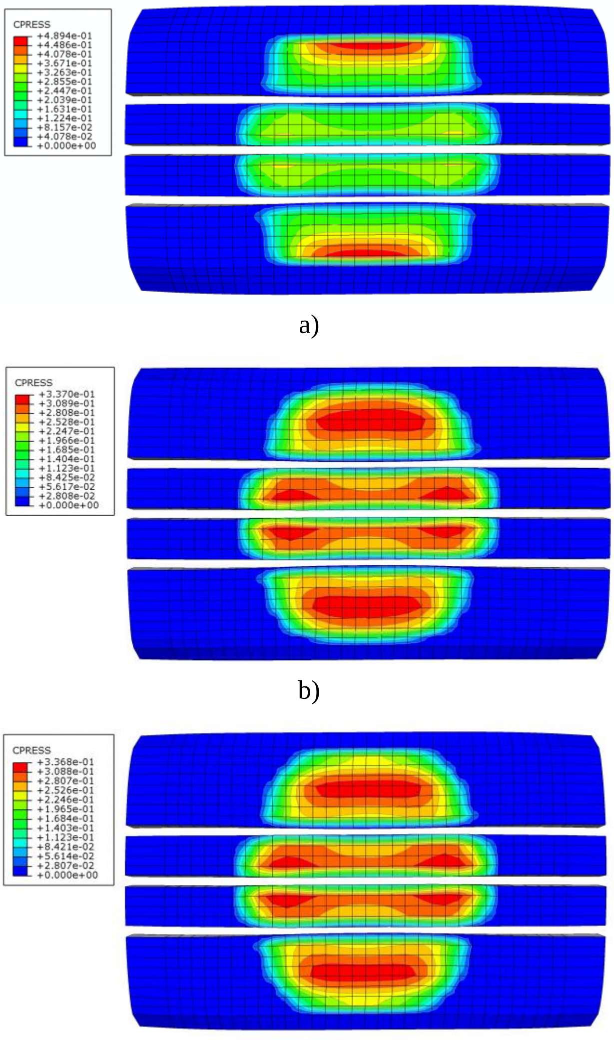


Fig. 4 Comparison of load-deflection curves for all tire variations

The most obvious effect of the sidewall radius variation may be seen in Fig. 5, which shows its influence on the contact stresses along the footprint at the given vertical load. Load intensity is chosen to be equivalent to the load acting on a tire mounted on a small passenger car, with four passengers aboard. The variation that contains the smallest sidewall radius is characterized by a distinct rise of the contact pressure in the area of tire shoulders. In comparison with two other variations, maximum value of contact stress at the footprint is also significantly higher which may lead to uneven and excessive tire wear.



a)

b)

c)

Fig. 5 Contact stress distribution at vertical load of 2750N for a) R1=53.8mm, b) R1=64.4mm and c) R1=75.0mm

3.2.3 Braking and acceleration

The changes of the chosen parameters do not significantly affect the behavior of the tire rolling on the straight line with action of acceleration or braking moment. The influence of the sidewall radius changes on the braking-to-acceleration curve, obtained by steady-state rolling analysis [7], may be seen in Fig. 6. The difference between the curves that correspond to the tire variations with different sidewall radius is very modest, but the braking stiffness of variations with a higher radius tends to be slightly larger. In the case of the belt width changes, the responses of corresponding tire instances are even closer to each other.

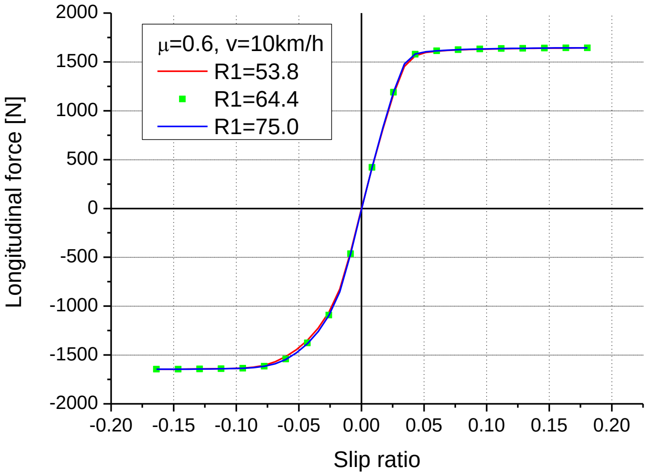


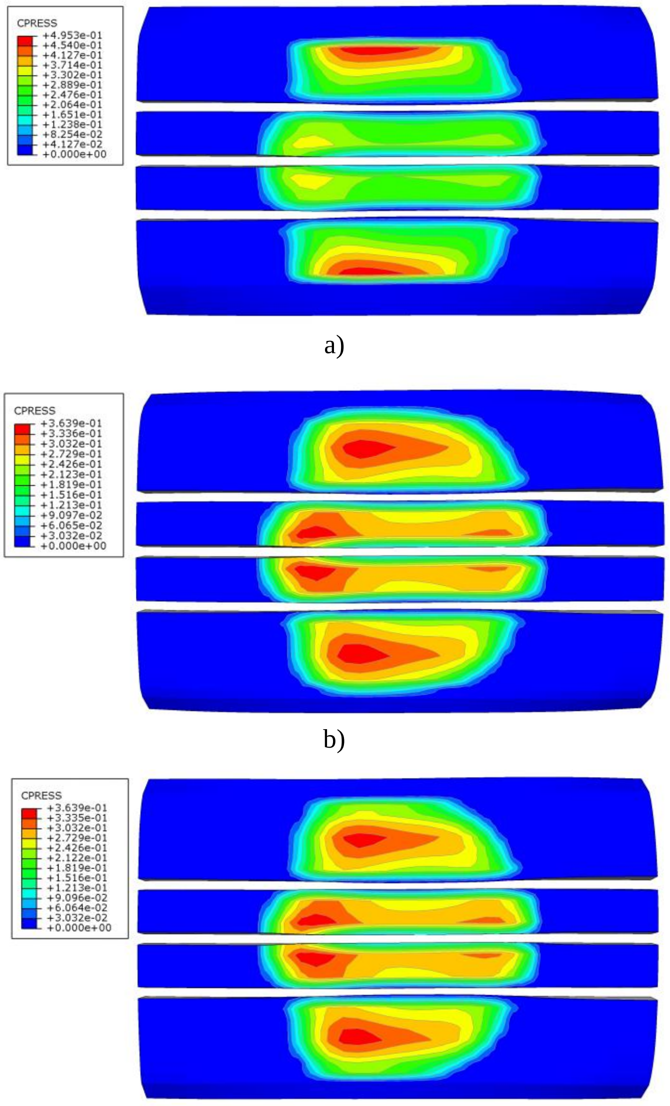
Fig. 6 The effect of sidewall radius variation on full-breaking–to–full-acceleration curve

The shape of the footprint and distribution of contact stress in the state of full braking, for different variations of sidewall radius, are shown in Fig. 7. As well as in the case when vertical load is applied, the distribution of contact stress is more even for second and third variation. Similar results are obtained when accelerating tire is analyzed.

3.2.4 Cornering

The results of the cornering analysis are also compared for all the proposed tire variations. The cornering curves for slip angle varying from -8 to 8 degrees are shown in Fig. 8. The cornering stiffness is higher for models with larger values of sidewall radius, i.e. they are more responsive to steering input. Nevertheless, the difference between the responses is very small. In the case of the belt width variation, it may be concluded that the belts widening produces greater cornering stiffness, while at higher slip angles the cornering response seems to be reversed. Narrowing of the belts produces the opposite effect.

Fig. 9 shows the comparison of footprint shape and contact stress distribution for the tire cornering at 2 and 4 degrees, respectively, for different variations of the sidewall radius. Stress distribution is more even for two variations with larger radius. The effect of the belt width changes is also noticeable but less significant.

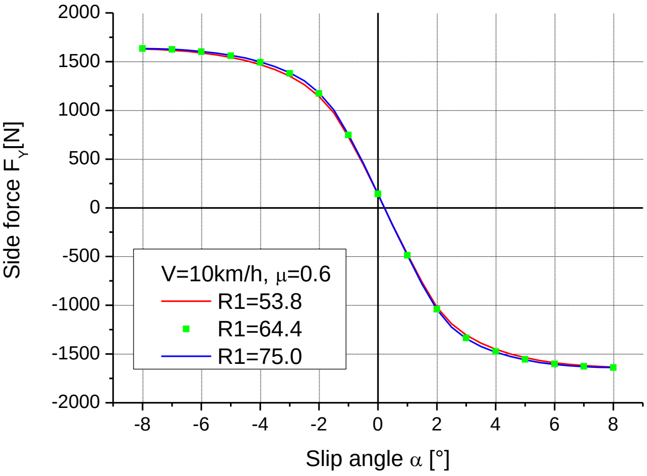


a)

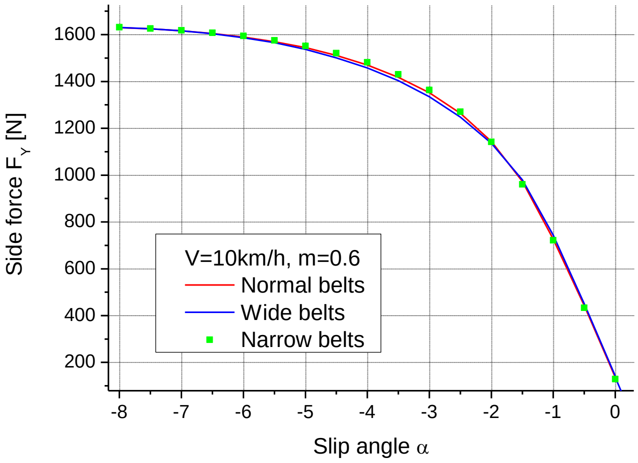
b)

c)

Fig. 7 Tire footprint shapes at full braking for
a) R_1=53.8mm, b) R_1=64.4mm and c) R_1=75.0mm



a)



b)

Fig. 8 Cornering curves for models with three different values of a) sidewall radius and b) belt width

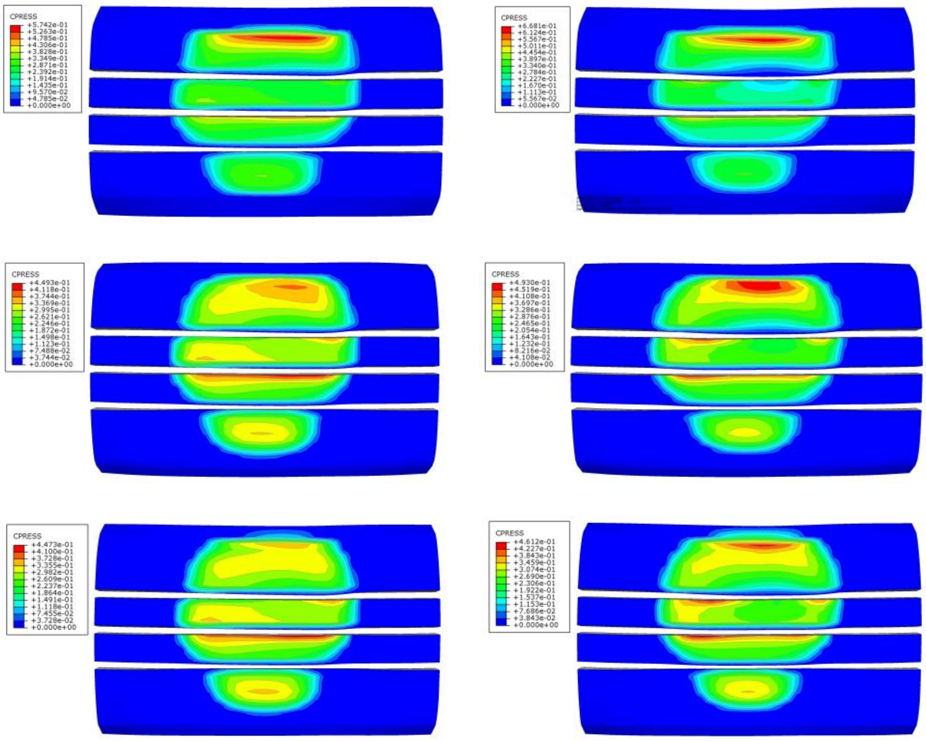


Fig. 9 Tire footprint shapes; first row: R_1=53.8 mm, second row: R_1=64.4 mm, third row: R_1=75.0 mm. Left column corresponds to cornering at 2 degrees and right column to cornering at 4 degrees

3.2.5 Best design

From the results presented above it may be concluded that tire variation having sidewall radius equal to 64.4 mm shows the best overall performance in terms of maneuverability and tire wear. While maintaining the smoothest distribution of contact pressure, it is characterized by improved cornering and braking stiffness. Widening of the belts also has a positive effect on the two considered criteria for evaluation of tire performance.

4. CONCLUSION

A parametric design study of tire profile shape and belt width is presented in order to illustrate the use of the proposed approach to the FEM application in tire design. The earlier reported studies have faced a bottleneck in the preprocessing phase and thus have taken into account only the influence of those design parameters that did not affect the shape of the finite element mesh. The new approach is more flexible as it facilitates the easy and automated changes of the FE mesh through the use of a specially designed CAD model and an originally developed mapping and translation code.

The presented study is a pilot one but it clearly demonstrates the advantages of the proposed approach. On one hand, it shows how a large number of design variations, each one geometrically different, could be analyzed in a very short time. On the other, it also leads to the improvement of the existing tire design in terms of footprint stress distribution and maneuverability.

In further research, dedicated CAD tire model and translation code will be used in the design of experiment phase of the tire design optimization process, to quickly and easily create the required number of FE tire models.

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PARAMETARSKA STUDIJA PROFILA PNEUMATIKA BAZIRANA NA MKE, UZ UPOTREBU NAMENSKOG CAD MODELA I PREVODIOCA PODATAKA

U radu je prikazana parametarska studija oblika profila i širine pojaseva pneumatika,bazirana na metodu konačnih elemenata (MKE). Jedna od glavnih prepreka na koju su naišli autori sličnih studija odnosi se na nemogućnost automatske promene mreže konačnih elemenata nakon promene geometrije pneumatika. Da bi se ovaj problem prevazišao ovde se predlaže novi pristup. On podrazumeva automatsku promenu mreže konačnih elemenata koja prati promenu konstruktivnih parametara na namenskom CAD modelu. Ažuriranje mreže moguće je zahvaljujući originalno razvijenom programu za mapiranje i prevođenje podataka. Na ovaj način moguće je za veoma kratko vreme analizirati performanse velikog broja geometrijski različitih varijanti konstrukcije pneumatika. Iako je u pitanju pilot studija, ona je u isto vreme doprinela i poboljšanju postojeće konstrukcije pneumatika.

Ključne reči: *Pneumatik, Parametarska studija, stacionarno kotrljanje, MKE, analiza primenom MKE*