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Oblikovanje dirkalnika

Developing a Racing Car

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V prispevku sta prikazani dve možnosti izboljšanja lastnosti dirkalnika Formula S. Eden najskladnejših načinov za dvig moči motorja je spretno oblikovan dovod zraka v motor. Zato je v prvem delu prispevka predstavljen postopek optimalnega oblikovanja sesalnega sistema. Postopek optimiranja temelji na uporabi metod matematičnega programiranja in pomeni učinkovit način za povečanje moči motorja v najbolj zanimivem področju obratovanja motorja. V drugem delu prispevka je pozornost posvečena novim zamislim izdelave celotnega dirkalnika. Za dosego vrhunskih rezultatov je treba narediti več, kakor le slediti konkurenci. Analiza postavitev glavnih agregatov je pokazala, da bi k večji okretnosti in stabilnosti dirkalnika pripomoglo to, da bi bil motor postavljen ob voznikovi strani. Optimiran sesalni sistem pomeni zanesljiv korak naprej v borbi za povečanje dejanske moči dirkalnika, kar je lahko uporabno takoj. Zasnova z bočno postavitvijo motorja pa predstavlja povsem novo pot razvoja dirkalnikov Formula S, kar bo morda prineslo dolgoročne prednosti.

(Ključne besede: dirkalni avtomobili, Formula S, razvoj, optimiranje, sistemi sesalni)

This article presents two approaches for improving a Formula S racing car. One of the best ways to increase the engine's power is to skillfully design the air- supply system of the engine. This is the reason why the first part of the paper is about the intake-manifold optimization procedure. The procedure relies on mathematical programming and offers a way to significantly increase the engine power in the most important engine regimes. In the second part of the paper, attention is focused on new concepts of building the racing car. In order to be the best it is necessary to do more than symply follow the competion. An analysis of the positions of the main components has shown that a racing car would be more agile and stable if the engine was to be mounted beside the driver. Optimizing the intake manifold represents one significant step forward in the struggle to increase the effective power of the car, which brings an immediate advantage. The new position concept, however, which also eliminates the differential drive, represents a completely new development in the design of the Formula S car that might bring us long-term benefits.

(Keywords: racing automobiles, Formula S, development, optimization, intake manifold)

0 UVOD

Na mnogih univerzah po vsem svetu se vsako leto znova zberejo skupine študentov, ki načrtujejo, oblikujejo, snujejo, tržno obdelajo in izdelajo malo enosedežno dirkalno vozilo. Vse te skupine študentov se enkrat na leto zberejo v Veliki Britaniji na tekmovanju Formula Student. Na Fakulteti za strojništvo v Mariboru že od leta 1999 vsako leto znova izdelamo nov dirkalnik, ki nosi ime Formula S. Rezultati prejšnjih let kažejo, da naša skupina vedno zaseda odlične uvrstitve. Je med prvimi v Evropi in skoraj vedno med peščico tistih, ki jim uspe dokončati vztrajnostno dirko, ki je vrhunec tekmovanja, (sl. 1).

Poglavitni namen tekmovanja Formula Student je vzbuditi pri študentih zanimanje za delo konstrukterjev in razvijati talente pri mladih ljudeh

0 INTRODUCTION

Every year, groups of university students around the world, conceive, plan, economically evaluate and manufacture a small single-seat racing car. All these groups compete once a year at on event in Great Britain called the Formula Student Competition. The Faculty of Mechanical Engineering in Maribor has built a car every year since 1999 called Formula S. The results from past years show that our team was always among the best in Europe and that our car always finished the endurance race, which is the prestige event of the competition, Fig. 1, among the first few finishers.

The basic intention of the Formula Student competition is to develop an interest in design work and to foster the talents of the students [1]. To

Sl. 1. *Dirkalnik Univerze v Mariboru Formula S v Veliki Britaniji leta 2002*
Fig. 1. *Formula S racing car from theUniversity of Maribor competing in Great Britain in 2002*

[1]. Zgolj v nekaj mesecih opraviti ves razvoj dirkalnega vozila je veliko delo, ki ga zmorejo le izjemno sposobni in marljivi študenti pod dobrim strokovnim vodstvom. Na tekmovanju se ocenjujejo tako zamisli, inženirske rešitve, spretnosti oblikovanja, vozne lastnosti dirkalnika in tudi ekonomsko ozadje projekta. Zato je vsako od naštetih področij zase predstavlja velik izziv za celotno skupino.

Prispevek obravnava dve področji dela skupine študentov mariborske Fakultete za strojništvo. Najprej je predstavljeno načrtovanje, snovanje in optimiranje sesalnega sistema. Potem pa so obravnavane možnosti izboljšave v osnovni zamisli celotnega dirkalnika.

1 OBLIKOVANJE SESALNEGA SISTEMA IN OPTIMIRANJE GLEDE NA NAJVEČJO MOČ

Dirkalnik Formula S ima motor vgrajen za voznikovim hrbtom. Poleg same lege motorja pomeni varnostni lok, ki ščiti voznikovo glavo, podpore varnostnega loka in lupina avtomobila (sl. 2), osnovne geometrijske omejitve pri oblikovanju sesalnega sistema.

Dirkalnik Formula S je opremljen z večtočkovnim sistemom za vbrizg goriva. Zahtevnik za oblikovanje sesalnega sistema je predstavljen v preglednici 1 [2].

1.1 Oblikovanje sesalnega sistema

Oblikovanje sesalnega sistema je v začetni fazi stvar iskanja konstrukcijskih rešitev v smislu, kam sploh postaviti določen element [3]. Običajno je del sesalnega sistema tudi zbiralnik. Mi ga nismo predvideli, ampak smo že v osnutku sledili zamisli,

develop a racing car in just a few months is a hard task that can only be done by exceptionally skilled and active students under expert guidance. During the competition, the ideas, the engineering solutions, the design skill, the driving characteristics of the car and the economic aspects of the whole project are evaluated. All these fields represent a big challenge for the whole group of students.

This paper deals with the two areas on which our students are working. In the first part the conceiving, the planning and the optimization of the intake system is presented. In the second part, the improvement to the conceiving phase of the whole vehicle is discussed.

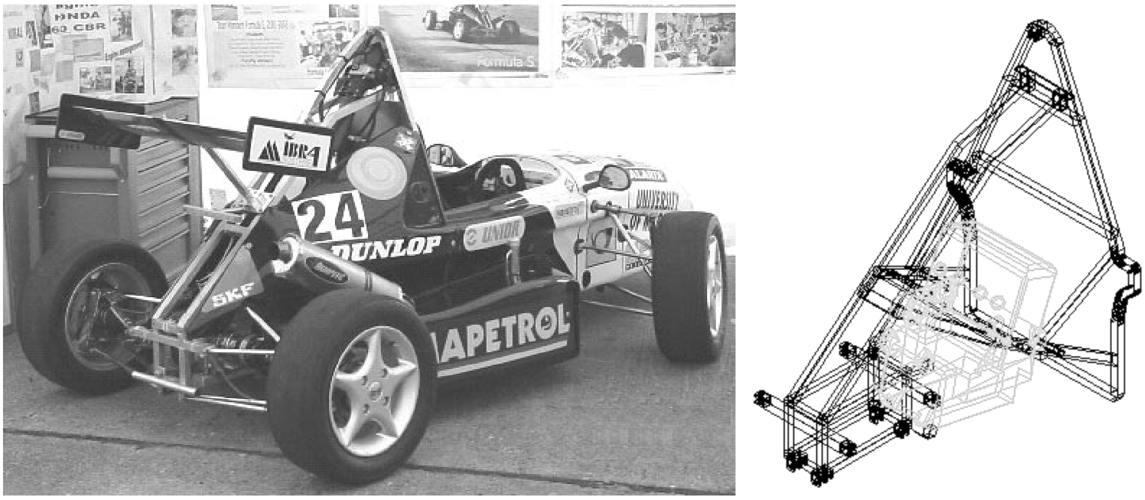
1 CONCEIVING THE INTAKE MANIFOLD AND ITS OPTIMIZATION IN TERMS OF MAXIMUM POWER

The engine of the Formula S racing car is positioned behind the driver's back. The basic geometry constraints that influence the shape of the intake manifold are, in addition to the engine's position, the main hoop that protects the driver's head, its brackets and the car body, Fig. 2.

The Formula S car is equipped with a multipoint fuel-injection system. The checklist relating to the manifold design is presented in Table 1 [2].

1.1 Conceiving the intake manifold

The first stage of the intake-manifold design is to look for the best positions for the parts [3]. The intake manifold usually also has an intake plenum. Instead of this, however, from the beginning it was decided to continually increase the cross-sectional



Sl. 2. *Motor Honda 600 cm³ stoji povprek v zadku dirkalnika*
Fig. 2. *The Honda 600 ccm engine is positioned crosswise in the rear of the car*

Preglednica 1. *Zahtevnik za sesalni sistem Formula S 2003*
Table 1. *Checklist relating to the intake manifold Formula S 2003*

Št. No.	Zahteve v zvezi z obliko sesalnega sistema Requirements concerning the manifold design	
1	Zajemalnik zraka nad glavo voznika Air capture is positioned above the driver's head	želja desired
2	Celotni sesalni sistem mora biti znotraj paličastega okvira dirkalnika The intake-manifold system is placed inside the racing car's space frame	obvezno required
3	Ves zrak, ki ga potrebuje motor, mora teči skozi en omejilnik premera 20mm The intake air is run through the restrictor with a 20-mm diameter	obvezno required
4	Omejilnik mora biti vgrajen med loputo in sesalno odprtino motorja The restrictor is positioned after the throttle and before the engine intake	obvezno required
5	Vsak valj motorja mora dobiti enako količino zraka Each cylinder gets an equal amount of air	obvezno required
6	Moč motorja naj bo prek 40kW The engine power is over 40 kW	želja desired
7	Sesalni vod naj daje čim manjši upor zraku, ki se po njem pretaka The intake manifold has a minimal resistance to air flow	želja desired

naj se prerez sesalnih kanalov od omejilnika do vstopa v motor zvezno povečuje. Osnutek sesalnega voda, ki izpolnjuje prve štiri zahteve iz zahtevnika, je predstavljen na sliki 3.

Da bi lahko izpolnili še preostale tri zahteve iz zahtevnika, je treba najprej analizirati, kaj se sploh dogaja z zračnim tokom, ki teče skozi predpostavljeni sesalni sistem. Ta korak pomeni osnovo za optimalno oblikovanje sesalnega sistema.

Analizo tokovnih karakteristik ustaljenega zračnega toka skozi sesalni vod smo naredili z uporabo paketa računske dinamike tekočin AVL FIRE [4], ki temelji na metodi končnih prostornin. V izračunu sta bili upoštevani enačba zzveznosti:

area of the intake manifold, from the restrictor to the engine input. The adopted concept that fulfilled the first four requirements from the check list is presented in Figure 3.

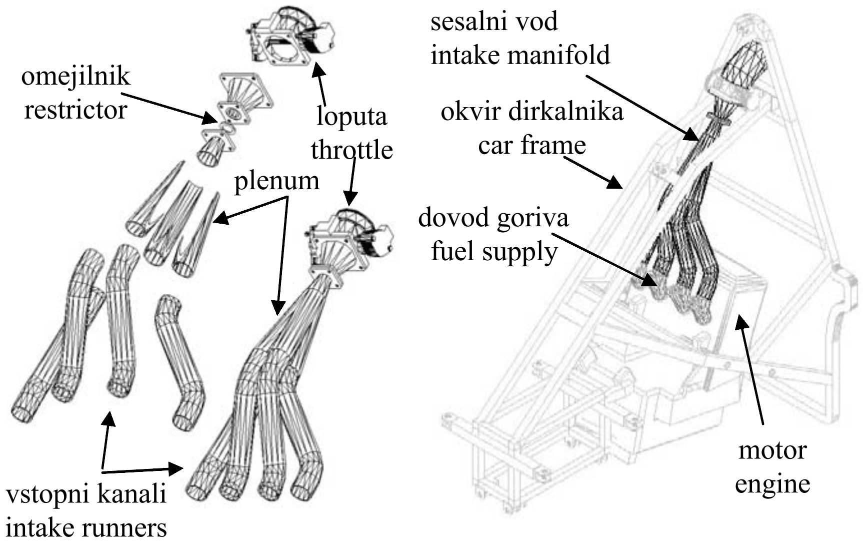
In order to fulfill the other three requirements it is necessary to analyze what actually happens to the air flow that streams through the manifold. This step forms the basis for the optimization of the manifold.

The analysis of a stationary air flow that runs through the intake manifold was made by the dynamic fluid computation package AVL FIRE [4], which is based on the finite-volumes method. The mathematical model is based on the continuity equation:

$$\frac{\partial \overline{p}}{\partial t}+\frac{\partial}{\partial x_j}\left(\overline{\rho}\cdot\overline{u}_j\right)=0 \qquad (1)$$

in gibalna enačba:

and the motion equation:



Sl. 3. *Osnutek sesalnega sistema, ki izpolnjuje prve štiri zahteve iz zahtevnika*
Fig. 3. *The concept of the intake manifold that fulfills the first four requirements from the check list*

$$\frac{\partial}{\partial t}\left(\bar{\rho}\cdot\bar{u}_i\right)+\frac{\partial}{\partial x_j}\left(\bar{\rho}\cdot\bar{u}_i\cdot\bar{u}_j+\bar{\rho}\cdot\overline{u_i^{'}\cdot u_j^{'}}-\bar{\tau}_{ij}\right)+\frac{\partial p}{\partial x_i}-\bar{\rho}\cdot g\frac{x_i}{|x|}=0 \quad (2),$$

kjer so: u_j - komponenta hitrosti v smeri kartezične koordinate x_j, p - tlak, ρ - gostota, τ_{ij} - pa tenzor napetosti.

Prenosni enačbi k-ε izbranega turbulentnega modela sta:

where u_j is the component of the velocity in the x_j Cartesian coordinate direction, p is the pressure, ρ is the density and τ_{ij} is the stress tensor.

The two transport equations of the chosen k-ε turbulent model are:

$$(u\cdot\nabla)k-\nabla\left[\left(\nu+\frac{\nu_t}{\sigma_k}\right)\nabla k\right]-G_k-G_b+\varepsilon+Y_M=0 \quad (3)$$

$$(u\cdot\nabla)\varepsilon-\nabla\left[\left(\nu+\frac{\nu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right]-C_1\frac{\varepsilon}{k}(G_k+C_3G_b)-C_2\frac{\varepsilon^2}{k}=0 \quad (4),$$

kjer so: ν_t - turbulentna viskoznost , G_k - nastajanje turbulentne kinetične energije, G_b - nastajanje turbulence zaradi gravitacije, Y_M - vpliv stisljivosti tekočine na turbulenco in C_1, C_2, C_μ, σ_k, σ_ε - izkustvene stalnice modela.

Oblika in izmere sesalnega sistema so bile na začetku predpostavljene po inženirskih izkušnjah. Robni pogoji so podani z nespremenljivim padcem tlaka, ki je značilen za sesalni sistem. Izvedena je bila numerična analiza predpostavljenega začetnega sesalnega sistema. Izračunali smo polja hitrosti, tlaka in turbulentne kinetične energije vzdolž sesalnega sistema. Kot vzorčni rezultat sta na sliki 4 prikazani hitrostni polji na površini kanalov, ki vodita zrak v prvi oziroma v drugi valj.

Slika 5 kaže, kako se spreminja prerez sesalnega sistema. Razvidno je, da se zrak bolj ali manj enakomerno razporedi v posamezne vstopne kanale.

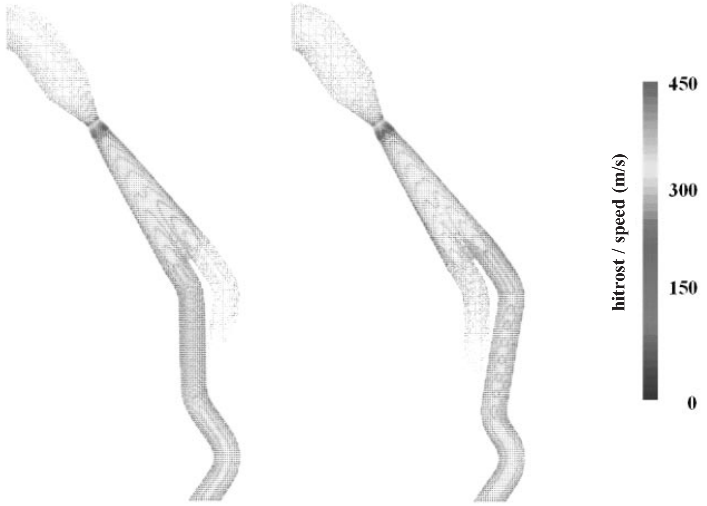
Sesalni vod je glede na podatke v preglednici 2 v osnutku odlično oblikovan, saj je razlika v količini zraka, ki prihaja v valje manj ko 1%. Porazdelitev zraka po valjih je torej enakomerna. Vbrizgalne ventile za gorivo

where ν_t is the turbulent viscosity, G_k is the production of turbulent kinetic energy, G_b is the turbulence production due to the gravitation, Y_M is the influence of the fluid compressibility on the turbulence and C_1, C_2, C_μ, σ_k, σ_ε are the empirical constants of the model.

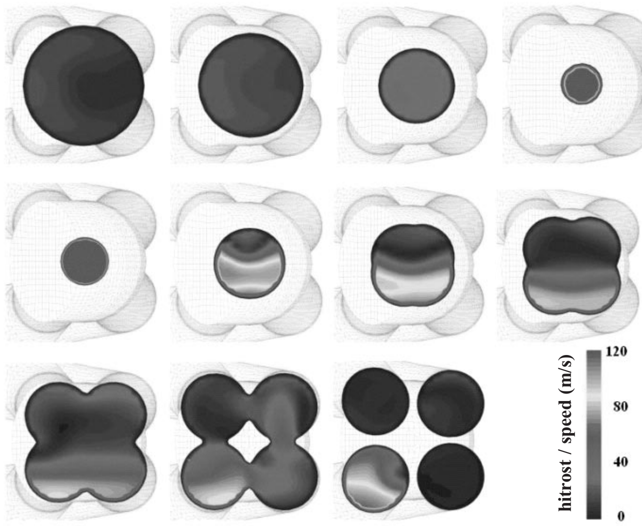
At the beginning the shape and the dimensions of the intake manifolds were estimated on the basis of engineering experience. The boundary conditions are defined by the constant drop of the air flow pressure, which is characteristic for the intake manifold. The initial intake manifold was numerically analyzed and the velocity fields, the pressure distribution and the turbulent kinetic energy distribution along the intake-manifold channels were calculated. Figure 4 presents the velocity fields of the two channels that lead the air flow to the first and the second cylinders.

Figure 5 shows the cross-section changes of the intake manifold. It is obvious that the air is more or less equally distributed among the individual intake channels.

The data in Table 2 suggest that the intake manifolds have an excellent design, because the difference in the quantity of air that goes into the individual cylinders is less than 1%. The air



Sl. 4. *Hitrostni polji na površini kanalov, ki vodita zrak v prvi in drugi valj*
Fig. 4. *The velocity fields on the surfaces of the channels that lead the air flow to the first and second cylinders*



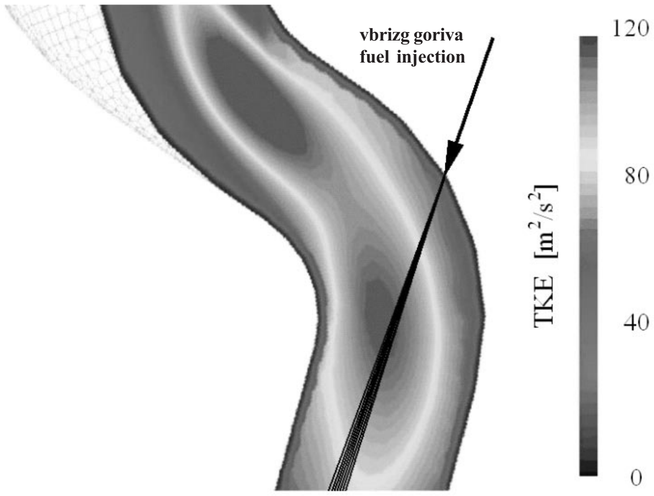
Sl. 5. *Hitrostno polje v značilnih prerezih sesalnega sistema*
Fig. 5. *The velocity fields in the characteristic cross sections of the intake manifold*

Preglednica 2. *Primerjava tokovnih značilnic med cevmi sesalnega sistema*
Table 2. *Comparison of the airflow characteristics between the pipes*

	cevi v valju 1 in 4 pipes 1 and 4	cevi v valju 2 in 3 pipes 2 and 3	razlika difference
pretok snovi, $\dot{m}$ v kg/s mass flow, $\dot{m}$ [kg/s]	0,0648	0,0653	0,77 %
hitrost, $\bar{v}$ v m/s velocity, $\bar{v}$ [m/s]	85,380	85,043	0,39 %

vgradimo tako, da curek goriva brizga v območje največjih hitrosti zraka ([4] in [5]). Zato je izbrana lega šob na zadnjem kolenu cevi sesalnega sistema, in sicer pod kotom 5° glede na središčno os vstopnih kanalov na motorju (sl. 6).

distribution among the cylinders is almost perfect. The injection valve has to be mounted so that the spray of fuel is directed into the field of the maximum air velocities ([4] and [5]). That is the reason why the fuel valve is positioned on the last pipe knee and inclined at an angle of 5° with respect to the central line of the intake channels, Figure 6.



Sl. 6. V*brizgalni ventil vbrizga gorivo v območje največjih hitrosti*
Fig. 6. *Injection valve sprays the fuel into the field of maximum velocities*

1.2 Izračun značilnic motorja

Za opis termodinamičnega postopka pri nespremenljivi vrtilni frekvenci v motorju je bil uporabljen program AVL Boost [6]. Tok snovi je obravnavan enorazsežno. Pretočne izgube na določenih mestih v motorju se upoštevajo z uporabo pretočnih koeficientov. Model delovanja motorja temelji na prvem zakonu termodinamike:

1.2 Calculation of the engine's characteristics

In order to describe the thermodynamics process at a constant engine speed, the AVL Boost [6] package was used. The material flow is described by a one-dimensional model. Flow losses at the particular locations are considered by taking into account the discharge coefficients. The model of the engine's activity is based on the first law of thermodynamics:

$$\frac{d\left(m_c \cdot u\right)}{d\alpha} = -p_c \cdot \frac{dV}{d\alpha} + \frac{dQ_f}{d\alpha} - \sum \frac{dQ_w}{d\alpha} - h_{BB} \cdot \frac{dm_{BB}}{d\alpha} \quad (5),$$

kjer člen na levi strani opisuje spremembo notranje energije znotraj valja, členi na desni pa delo bata, dovedeno toploto goriva, izgubo toplote na stenah in entalpijski tok.

Predpostavljeno je, da je mešanica goriva in zraka povsem homogena, kar pomeni, da je razmerje med zrakom in gorivom med postopkom zgorevanja vedno enako, pa tudi, da sta tlak in temperatura med zgorelim in nezgorelim delom zmesi vedno enaka:

where the term on the left-hand side of the equation describes the change of the internal energy inside in the cylinder, while the terms on the right-hand side of the equation represent the piston work, the heat release energy from the fuel, the heat losses through the cylinder liners and the enthalpy flow.

It is supposed that the air and the fuel mixture is perfectly homogenous, which, as a result, means that the relation between the air and the fuel during the burning process is always constant. Consequently, the pressure and the temperature in the burned as well as in the unburned mixture are the same:

$$\frac{dT_c}{d\alpha} = \frac{1}{\left(m_c \frac{\partial u}{\partial T} + \frac{m_B p_c}{T_c} \cdot \frac{\partial u_B}{\partial p}\right)} \cdot \left[\begin{array}{l} \frac{dQ_f}{d\alpha}\left\{1 + \frac{1}{H_u}\left(u_F + \lambda L_{ST} u_{Air} - (1+\lambda L_{ST})\left[u_B + p_c \frac{\partial u_B}{\partial p}\right]\right)\right\} - \frac{dQ_W}{d\alpha} \\ - p_c \frac{\partial V_v}{\partial \alpha}\left(1 - \frac{m_B}{V_c}\frac{\partial u_b}{\partial p}\right) - \frac{dm_{BB}}{d\alpha}\left(h_{BB} - u_c - p_c \frac{m_B}{m_c}\frac{\partial u_B}{\partial p}\right) \end{array} \right] \quad (6),$$

kjer so: T_C in p_C - temperatura in tlak znotraj valja, m_C, m_B in m_{BB} - masa zmesi v valju, masa zgorelega dela zmesi in masa zmesi, ki uide med batom in steno valja, α - kot zasuka ročične gredi, u, u_B, u_F in u_{Air} - specifična notranja energija, notranja energija zgorelega dela zmesi, notranja energija goriva in zraka. H_u - je spodnja kalorična vrednost, Q_f - energija goriva, λ - razmernik zraka, L_{ST} - stehiometrično razmerje, Q_w - izguba toplote na steni in h_{BB} - entalpija zmesi, ki uide med batom in steno valja.

where T_C and p_C are the temperature and the pressure inside the cylinder, m_C, m_B and m_{BB} are the mass of the mixture in the cylinder, the burned mass of the mixture, and the escaped mass of the mixture that leaks away through the gap between the piston and the liner, α is the angle of the crankshaft rotation, u, u_B, u_F and u_{Air} are the specific inner energy, the inner energy of the burned mixture, the inner energy of the fuel and the inner energy of the air. H_u is the lowest caloric value, Q_f is the fuel energy, λ is the air ratio, L_{ST} is stehiometric ratio, Q_w the heat loss on the liner and h_{BB} is the enthalpy of the mixture that escapes through the gap between the piston and the liner.

V izračunu je upoštevana tudi plinska enačba:

The gas equation is also involved in the calculation procedure:

$$p_c = \frac{1}{V} \cdot m_c \cdot R_0 \cdot T_c \quad (7),$$

kjer je R_0 splošna plinska stalnica.

where R_0 is the general gas constant.

V našem primeru simuliranja delovanja motorja so bile izbrane naslednje funkcije. Za določitev sproščene toplote je bila uporabljena funkcija "Vibe":

In our engine simulation the following formulas were chosen. To describe the heat release the so-called 'Vibe' function was used:

$$\frac{dx}{d\alpha} = \frac{a}{\Delta\alpha_c} \cdot (m+1) \cdot y^m \cdot e^{-ay^{(m+1)}} \quad (8)$$

$$dx = \frac{dQ}{Q} \quad (9)$$

$$y = \frac{\alpha - \alpha_0}{\Delta\alpha_c} \quad (10),$$

kjer so: Q - toplotna vrednost dovedenega goriva, a - koeficient "Vibe" (popolno zgorevanje: 6,9), m - koeficient oblike, α, α_0 in $\Delta\alpha_c$ - kot zasuka ročične gredi, začetek in trajanje zgorevanja.

where Q is the heat value of the intake fuel, a is the 'Vibe' (perfect burning: 6.9) coefficient, m is the coefficient of the shape, α, α_0 and $\Delta\alpha_c$ are the angle of the crankshaft rotation, the angle of the combustion start and the angle of the combustion duration.

Prenos toplote je bil znotraj valja računan s funkcijo "Woschni 1978":

The heat exchange inside the cylinder was calculated using the formula "Woschni 1978":

$$\alpha_W = 130 \cdot D^{-0,2} \cdot p_c^{0,8} \cdot T_c^{-0,53} \cdot \left[C_1 \cdot c_m + C_2 \cdot \frac{V_D \cdot T_{c,l}}{p_{c,l} \cdot V_{c,l}} \cdot (p_c - p_{c,o}) \right]^{0,8} \quad (11),$$

kjer so: α_w - koeficient prenosa toplote na stenah valja, D - premer bata, c_m - srednja hitrost bata, V_d - delovna prostornina enega valja, $p_{c,0}$ - čista kompresija, $p_{c,1}$ in $T_{c,1}$ - tlak in temperatura znotraj valja v trenutku zaprtja sesalnega ventila, C_i - pa numerične stalnice.

where α_w is the coefficient of heat transfer through the liner walls, D is the piston diameter, c_m is the mean piston velocity, V_d is the working displacement of one piston, $p_{c,0}$ is the pure compression, $p_{c,1}$ and $T_{c,1}$ are the pressure and the temperature inside the cylinder at the moment of the intake valve closing, while C_i is a numerical constant.

Sproščanje toplote v kanalih je bilo opisano z uporabo funkcij "Zapf" za sesalno in za izpušno stran:

The heat release in the channels was described by using the "Zapf" formulae for the intake side and the exhaust side respectively:

$$\alpha_p = \left[C_7 + C8 \cdot T_u - C9 \cdot T_u^2 \right] \cdot T_u^{0,33} \cdot \dot{m}^{0.68} \cdot d_{vi}^{-1,68} \cdot \left[1 - 0,765 \cdot \frac{h_v}{d_{vi}} \right] \quad (12)$$

$$\alpha_p = \left[C_4 + C_5 \cdot T_u - C_6 \cdot T_u^2 \right] \cdot T_u^{0,44} \cdot \dot{m}^{0.5} \cdot d_{vi}^{-1,5} \cdot \left[1 - 0,797 \cdot \frac{h_v}{d_{vi}} \right] \quad (13),$$

kjer so: α_p - koeficient prenosa toplote skozi sesalne oziroma izpušne kanale, $\dot{m}$ - masni pretok, T_u - temperatura na vstopu v kanal, d_{vi} in h_v - premer sedeža ventila in njegov dvig.

where α_p is the coefficient of heat transfer through the intake/exhaust channels, $\dot{m}$ is the mass flow, T_u is the temperature on the channel input side, d_{vi} and h_v are the valve seat diameter and the valve lift, respectively.

Za potrditev omenjenega enorazsežnega modela motorja smo izračunane rezultate primerjali z izkustveno dobljenimi rezultati (sl. 7).

In order to verify the one-dimensional model above, the calculated results were compared to the experimental data, Figure 7.

Kakor je razvidno, so razlike med preskusom in numeričnimi izračuni zelo majhne. Zaradi tega lahko predpostavimo, da je opisan numerični model motorja dovolj zanesljiv in ga lahko vključimo v postopek optimiranja sesalnega sistema.

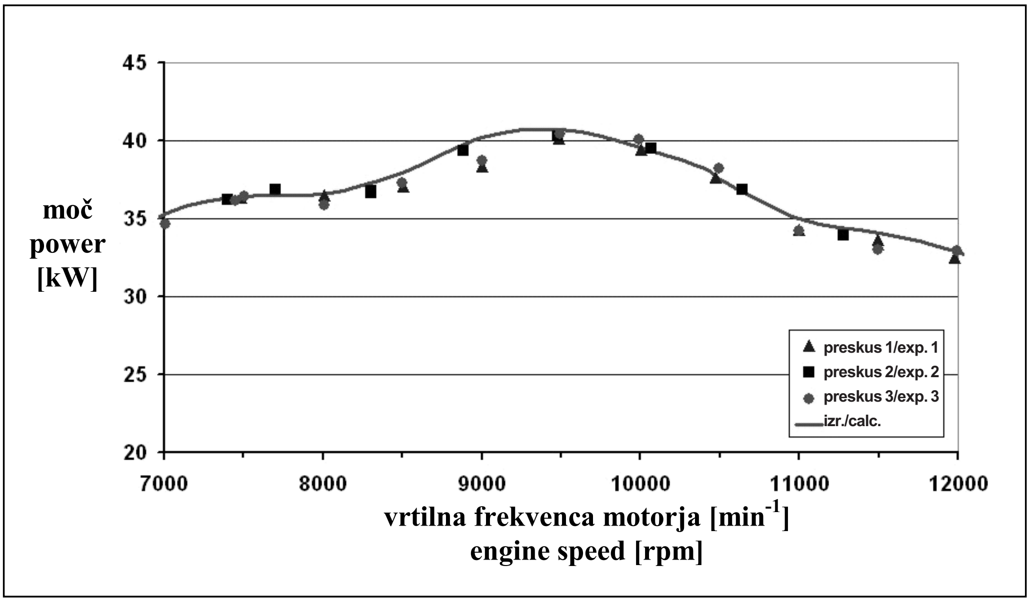
As can be seen, the differences between the experiment and the numerical calculations are rather small. Therefore, one can assume that the described numerical engine model is good enough to be employed for the intake-manifold optimization.

1.3 Optimiranje sesalnega sistema

1.3 The intake-manifold optimization

Obliko sesalnega sistema pustimo takšno, kakršna je bila predpostavljena v začetnem osnutku,

The basic form of the intake manifold was taken from the initial concept because it was clearly evident



Sl. 7. *Izmerjena in izračunana (izr.) dejanska moč motorja*
Fig. 7. *Measured and calculated (calc.) effective engine power*

saj je dokazano, da je polnjenje valjev enakomerno. Spreminjamo le izbrane izmere. Zamisel je bila taka, da določimo njihove optimalne vrednosti, tako da čimbolj povečamo moč motorja v najbolj pomembnih delovnih področjih obratovanja motorja.

that this shape ensures equal loading of the mixture for each cylinder. Some of the manifold dimensions, however, can still be changed. The idea now is to determine the optimum values for these dimensions so that the engine power will be increased as much as possible in the most important operating regimes of the engine.

1.3.1 Problem optimalnega projektiranja

1.3.1 The problem of optimum design

Problem optimalnega projektiranja lahko zapišemo v naslednji obliki:

The problem of optimum design can be written in the following form:

$$\min \hat{g}_0(\mathbf{b},\mathbf{u}) \quad (14)$$

ob upoštevanju pogojev

subject to the constraints:

$$\hat{g}_i(\mathbf{b},\mathbf{u}) \le 0, \; i = 1,..., j \quad (15)$$

in enačbe stanja

and the response equation:

$$\dot{\mathbf{u}} = \hat{f}(\mathbf{b},t,\mathbf{u}), \; \mathbf{u}\big|_{t=0} = \mathbf{u_0} \quad (16),$$

kjer je $\mathbf{b} \in \mathrm{R}^n$ vektor projektnih spremenljivk. Vektor $\mathbf{u} \in \mathrm{R}^m$ označuje odzivne spremenljivke, ki opisujejo odziv sistema, $\dot{\mathbf{u}} \in \mathrm{R}^m$ so njihovi časovni odvodi, t je časovna spremenljivka. Enačba stanja (2.16) označuje odvisnost $\mathbf{u}$ od t in $\mathbf{b}$. Skalarne funkcije $\hat{g}_0$ in $\hat{g}_i$ označujejo namensko in omejitvene funkcije. Namenska funkcija je odvisna od kakovosti oblikovanja $\mathbf{b}$, medtem ko omejitvene funkcije odsevajo mehanske, tehnološke in druge omejitve. Simbol n označuje število projektnih spremenljivk, m število odzivnih spremenljivk in j število omejitev. V našem primeru so funkcije $\hat{g}_0$ in $\hat{g}_i$ odvedljive po $\mathbf{b}$ in projektne spremenljivke so zvezne, zato je problem optimalnega projektiranja

where $\mathbf{b} \in \mathrm{R}^n$ is the vector of the design variables. The vector $\mathbf{u} \in \mathrm{R}^m$ denotes the response variables that describe the response of the system, $\dot{\mathbf{u}} \in \mathrm{R}^m$ are their time derivates and t is the time variable. The response equation (2.16) establishes the dependence of $\mathbf{u}$ on t and $\mathbf{b}$. The scalar functions $\hat{g}_0$ and $\hat{g}_i$ denote the objective and constraint functions respectively. The objective function depends on the quality of the design, meanwhile the constraint functions reflect the mechanical, technological and other constraints. The symbol n denotes the number of design variables, m denotes the number of response variables and j denotes the number of constraints. In our case the functions $\hat{g}_0$ and $\hat{g}_i$ are differentiable with respect to $\mathbf{b}$ and the design variables are continuous. Therefore, the problem mogoče reševati z uporabo približne metode kot ene izmed gradientnih metod matematičnega programiranja.

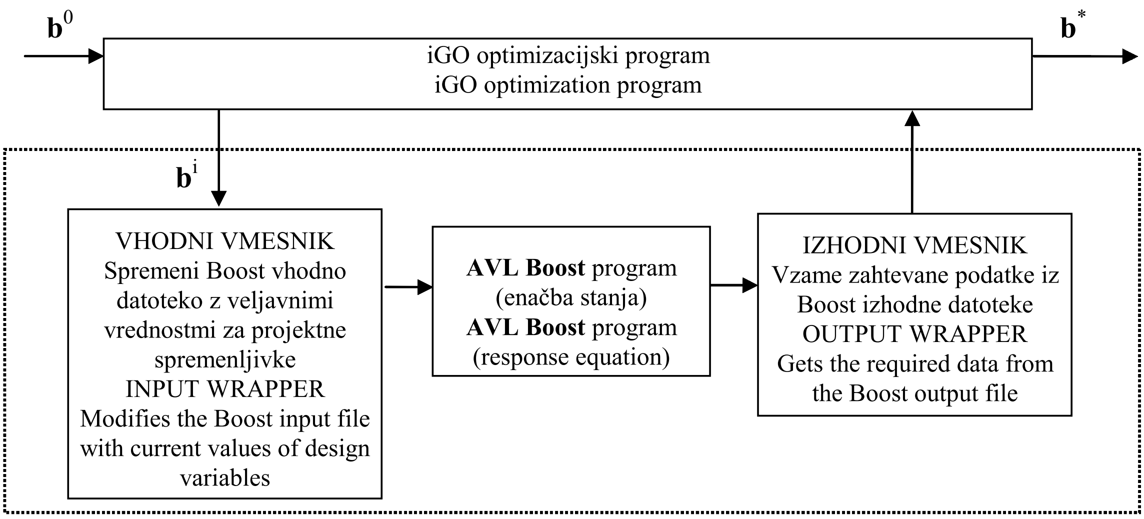
of optimum design can be solved by using an approximation method, which is one of the gradient methods of mathematical programming

1.3.2 Postopek optimalnega projektiranja

Za reševanje problema optimalnega projektiranja je bil uporabljen program iGO, ki je bil razvit na temelju približne metode ([7] in [8]). Pravzaprav iGO zaganja zunanje programe – tako imenovane simulatorje – za določitev vrednosti namenske in omejitvenih funkcij. Potem kliče svoj lastni optimizator za izboljšanje vrednosti projektih spremenljivk. Celoten iteracijski postopek reševanja problema optimalnega projektiranja je prikazan na sliki 8.

1.3.2 The optimum design procedure

To solve the optimum design problem, the program iGO was employed. This is a stand-alone program containing the approximation method described in ([7] and [8]). Essentially, iGO runs external programs – called simulators – in order to get the values of the objective and constraint functions. After that it calls its own built-in optimizer to improve the values of the design variables. This procedure is then repeated iteratively as shown in Figure 8.



Sl. 8. *Postopek reševanja problema optimalnega projektiranja*
Fig. 8. *The procedure for solving the optimum design problem*

1.3.3 Optimalno projektiranje sesalnega voda

Kot projektni spremenljivki v problemu optimalnega projektiranja se pojavljata premer *d* in dolžina *L* primarnih cevi sesalnega sistema:

1.3.3 Optimum design of the intake manifold

The design variables in the problem of optimizing the intake-manifold design are the diameter *d* and the length *L* of the manifold intake pipes:

$$\mathbf{b} = [d, L]^T \qquad (17).$$

Začetne vrednosti projektnih spremenljivk so bile določene z geometrijskimi merami predpostavljenega sesalnega sistema $b_1^{(0)} = 37\text{mm}, b_2^{(0)} = 340\text{mm}$. Zaradi možnosti takojšnje vgradnje sesalnega sistema v sedanji dirkalnik, je bilo treba glede na spreminjanje geometrijske oblike primarnih cevi, spreminjati tudi geometrijsko obliko difuzorja, tako da je skupna dolžina sesalnega sistema ostala nespremenjena.

Ker smo želeli povečati moč motorja, je bila namenska funkcija definirana kot vsota moči pri posameznih vrtilnih frekvencah, pomnožena z ustreznimi utežnimi faktorji. Karakteristične vrtilne frekvence so bile določene glede na pogoje vožnje. Tako lahko namensko funkcijo zapišemo kot:

The initial values of the variables are taken from the basic intake-manifold form as follows $b_1^{(0)} = 37\text{mm}, b_2^{(0)} = 340\text{mm}$. In order to ensure proper fitting of the intake manifold into the racing car, it is necessary to change the geometry of the manifold in such a way that the total length of the intake manifold does not change.

Since we want to increase the power of the engine, the objective function was defined as the sum of the individual engine powers at the corresponding rotation speeds and multiplied by appropriate weighting factors. The characteristic rotation speeds were selected according to the driving regime. As a result, the objective function can be written as follows:

$$g_0 = -\sum_{z=1}^{N} \psi_z P_{e,z} \quad (18),$$

kjer oznake ψ_z, z = 1, ..., N označujejo utežne faktorje za N posameznih delovnih režimov, medtem ko $P_{e,1}$, $P_{e,2}$ ..., $P_{e,N}$ označujejo dejansko moč na posameznem delovnem režimu. Z minimiziranjem vsote v enačbi (2.18) se pričakuje povečanje moči motorja.

Zahtevani pogoji, ki morajo biti izpolnjeni pri optimiranju sesalnega sistema, se nanašajo na celotno dolžino cevi L (najmanjša dolžina cevi L_{min}), specifično porabo goriva $g_{e,z}$ (največja dovoljena poraba $g_{e,max}$ = 350 g/kWh), hrup ζ (največji dovoljeni hrup ξ_{max} = 110 dBA) in na projektne spremenljivke 20 mm < b_1 < 60 mm in 300 mm < b_2 < 400 mm. Te omejitve lahko zapišemo kot:

where the symbols ψ_z, z = 1, ..., N denote the weighting factors for N individual operating regimes, meanwhile the symbols $P_{e,1}$, $P_{e,2}$ ..., $P_{e,N}$ denote the effective powers for individual operating regimes. By minimizing the sum defined in (2.18) it is possible to increase the engine's power.

The constraints that should be taken into account during the optimization are related to the total pipe length L (the minimum pipe length is L_{min}), the specific fuel consumption $g_{e,z}$, (the maximum allowed fuel consumption is $g_{e,max}$ = 350 g/kWh), the noise ζ (the maximum allowed noise is ξ_{max} = 110 dBA) and to the design variables 20 mm < b_1 < 60 mm as well as 300 mm < b_2 < 400 mm. These constraints can be written as:

$$\begin{aligned} &L_{\min} - L \le 0 \\ &g_{e,z} - g_{e,\max} \le 0, \;\; z = 1,\dots,N \\ &\xi_z - \xi_{\max} \le 0, \;\; z = 1,\dots,N \\ &b_i^L < b_i < b_i^U, \;\; i = 1,\dots,n \end{aligned} \quad (19).$$

Rezultati optimiranja so prikazani na sliki 9. Moč motorja z začetno obliko sesalnega sistema je izračunana na podlagi začetnih izbranih vrednosti projektnih spremenljivk, kakor je bilo dejansko izdelano. Moč motorja z optimiranimi vrednostmi projektnih spremenljivk L = 310,2 mm in d = 40,6 mm je v celotnem zanimivem delovnem področju motorja precej izboljšana. Pri tem so bili vsi pogoji (19) izpolnjeni. Na sliki 10 sta prikazani obe obliki sesalnega sistema.

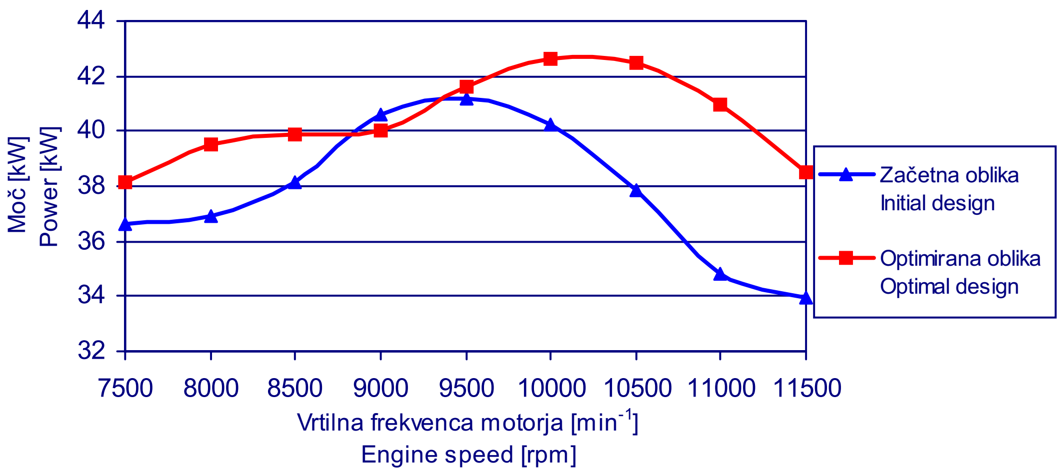
The results of the optimization are shown in Figure 9. The initial design corresponds to the actually manufactured manifold. As can be seen, the optimized values of the design variables L = 310.2 mm and d = 40.6 mm significantly increase the engine's power across the whole working range of the engine. The conditions defined in (19) remained fulfilled. Figure 10 shows both forms of intake manifold.

2 SPREMINJANJE OSNUTKA DIRKALNIKA

Konstrukcijski prijemi, kakor je pravkar obdelano optimiranje sesalnega sistema, dajo dirkalniku novo kakovost, toda za še odločilnejše izboljšanje lastnosti vozila je treba poseči v

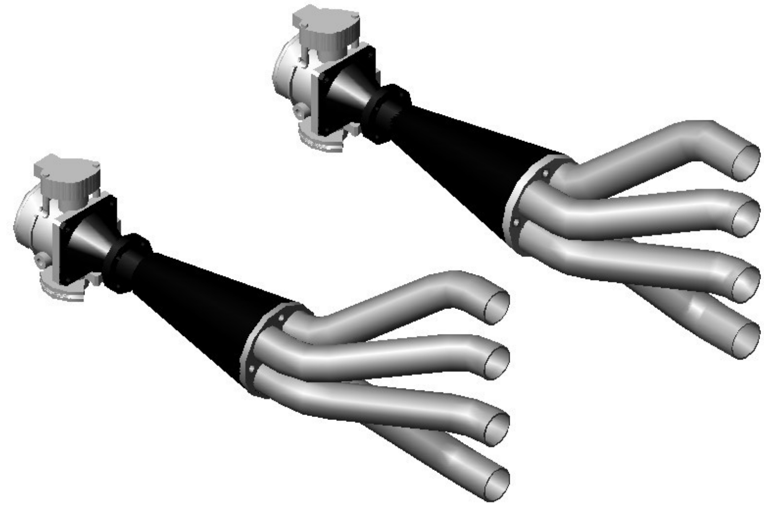
2 CHANGING THE BASIC RACING CAR CONCEPT

The design approach, such as the already described optimization procedure for the intake manifold, gives the car new quality, but to get more effective properties of the car it is necessary to intervene in the



Sl. 9. *Moč motorja se poveča z optimiranjem izmer in oblike sesalnega voda*

Fig. 9. *By optimizing the dimensions and the shape of the intake manifold the engine power is increased significantly*



Sl. 10. *Začetna in optimirana oblika sesalnega voda*
Fig. 10. *Initial and final shapes of the intake manifold*

zgodnejše faze razvoja. Oblika dirkalnika je deloma odvisna od pravilnika organizatorja tekmovanja, v veliki meri pa od znanja in hrabrosti ustvarjalcev. Kako dober bo dirkalnik, je odvisno od dobrega osnutka. Najučinkovitejša metoda za oblikovanje dobrega dirkalnika je poleg zbiranja lastnih izkušenj

earlier design phases. The shape of the racing car only partly depends on the competition's regulations. Thus, the biggest influence on the shape depends on the knowledge and the courage of the creators themselves. The quality of the racing car mostly depends on the quality of the basic concept. The most effective methods

Preglednica 3.1. *Zahtevnik za dirkalnik Formula S*
Table 3.1. *Conceptual check list for the Formula S racing car*

Št. No.	Zahteve v zvezi z gradnjo jeklenega okvirja Requirements concerning the steel chassis	
1	Avtomobil mora imeti tri varnostne loke The car has three safety hoops	obvezno required
2	Ob strani naj voznika varujejo vsaj tri cevi At least three tubes are on the driver's side in order to protect him	obvezno required
3	Glavni lok, ki varuje voznikovo glavo, mora biti podprt The main hoop that protects the driver's head is fixed by two brackets	obvezno required
4	Lok, ki je nad koleni, mora biti podprt z dvema podporama The front hoop toprotect the driver's knees is fixed by two brackets	obvezno required
5	Prednji lok mora biti podprt z dvema podporama The hoop to protect the driver's foot is fixed by the two brackets	obvezno required
6	Avtomobil mora biti opremljen z mečkalno cono dolžine 150 mm The car is equipped with a crush zone that has a length of 150 mm	obvezno required
7	Hram goriva mora biti vgrajen znotraj okvirja The fuel tank is placed inside the chassis members	obvezno required
8	Najmanjši premer platišča je 10" The minimum wheel diameter is 10"	obvezno required
9	Najkrajše medosje je 1525 mm The shortest wheelbase is 1525 mm	obvezno required
10	Kolesa naj bodo čim manjšega premera The wheel dynamics diameter is as small as possible	želja desired
11	Medosje naj bo čim bliže najkrajšemu The wheelbase is as close to the minimum wheelbase as possible	želja desired
12	Avtomobil naj bo čim krajši The length of the racing car is as short as possible	želja desired
13	Težišče avtomobila naj bo čim nižje The center of gravity of the car is as low as possible	želja desired

tudi analiza dobrih lastnosti vozil, ki so bila najboljša v dosedanjih tekmovanjih. Zahtevnik, preglednica 3, je nastal iz lastnih izkušenj, opazovanj konkurenčnih vozil in zahtev organizatorja [2].

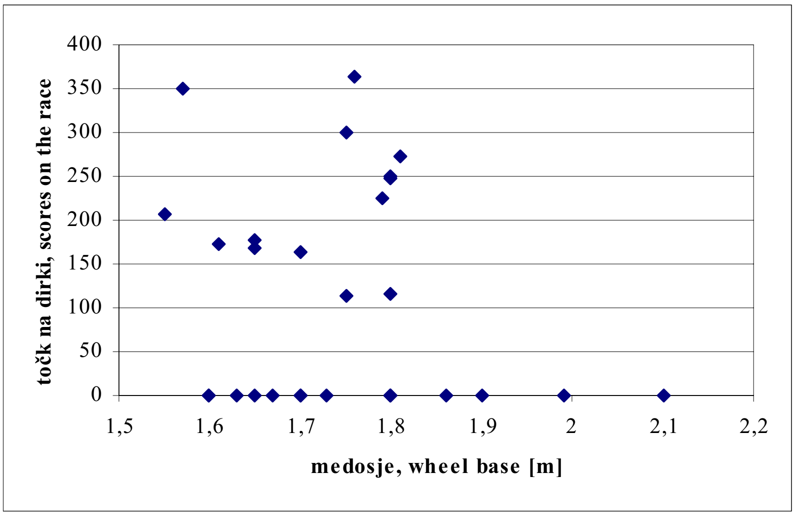
Analiza konkurenčnih vozil je pomagala do ugotovitve, da dolga vozila - tudi naša Formula S je bila dolgo vozilo - niso uspešna (sl. 11), zato smo iskali zamisel, kako vozilo skrajšati.

Očitno je postalo, da bi dirkalnik (sl. 12a) lahko zelo skrajšali s premikom motorja ob bok voznika (sl. 12b). Da ne bi povečali širine vozila, bi bilo treba voznika premakniti s sredine vozila na levo stran. Na ta način bi dobili morda celo prekratko vozilo, zato bi lahko uvedli še dodatno poenostavitev, tako da bi zadnji kolesi pomaknili bliže skupaj in se izognili diferencialnemu gonilu, celotna dolžina vozila pa bi se le malo podaljšala (sl. 12c).

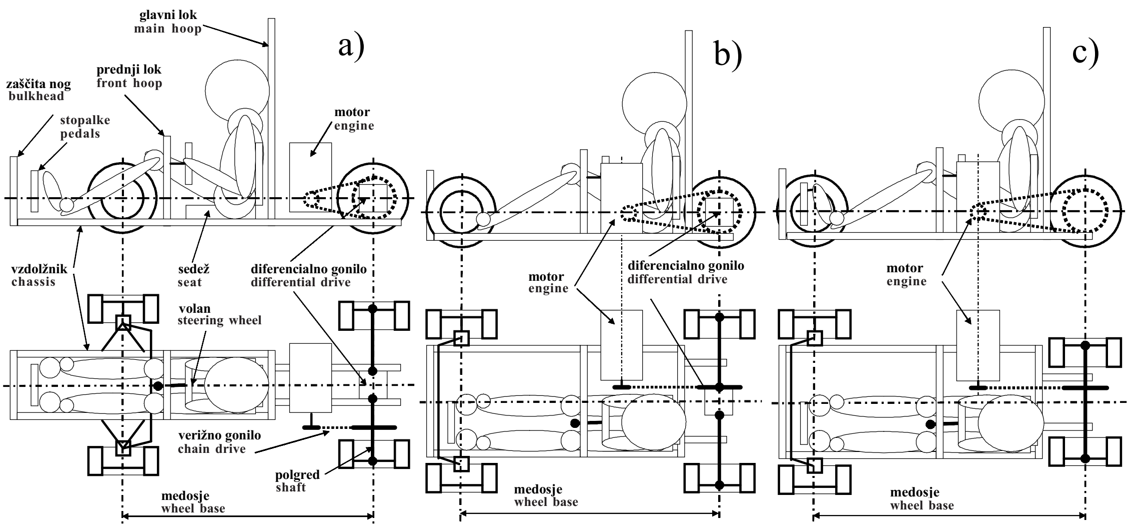
for conceiving a good racing car are collecting our own experiences and analyzing the cars that were the best in previous competitions. The check list that is formed on the basis of our own experiences, looking at competitors and the competition rules [2] is presented in Table 3.

The analysis of other racing cars helped us to discover that long vehicles (and our car was also a long vehicle) were not successful, Figure 11. Therefore, we started to look for fresh ideas as to how to shorten the vehicle effectively.

It became obvious that the most effective way to shorten the car, Fig. 12a, was to move the engine next to the driver. In order to make this possible, the driver should be moved from the central line of the vehicle to the left-hand side of the vehicle. With this modification we can achieve such a short vehicle that we have the possibility to introduce additional simplifications: we can shift the rear wheels closer to the central line in order to avoid the need for a differential drive. This would increase the total length of the vehicle, but only by a small amount, Fig. 12c.



Sl. 11. *Odvisnost medosja in števila točk na dirki (Formula Student 2002)*
Fig. 11. *The relationship between the wheelbase and the numbers of scores in the race (Formula Student 2002)*



Sl. 12. *Postavitev motorja v dirkalniku Formula S*
Fig. 12. *Fitting the engine into the Formula S racing car*

Med zelo pomembne značilnosti dirkalnika spada tudi velikost platišč, zato smo hoteli tudi to izhodišče utemeljiti z analizo konkurenčnih dirkalnikov. V nasprotju s prepričanjem, da morajo biti kolesa čim manjša, ker so potem tudi lažja, so štiri najboljše ekipe imele avtomobile opremljene s 13-palčnimi platišči, ker večja platišča pomenijo boljše vozne lastnosti dirkalnika. To je dovolj močan argument, da lahko tudi ekipa Univerze v Mariboru še dalje ostane pri 13-palčnih platiščih.

Velja prepričanje, da dirkalnik mora imeti karoserijo, saj prav neka lupina, ki je narejena iz pločevine ali umetne snovi, ojačene s steklenimi, ogljikovimi ali aramidnimi vlakni, daje avtomobilu obliko. Toda takšna karoserija je lahko težka od 15 do 25 kg. To je lahko kar 7 ali še več odstotkov skupne mase. Prav zato smo se odločili, da z novim osnutkom drastično zmanjšamo tudi maso karoserije, in sicer tako, da bo karoserija narejena iz blaga. Karoserija dirkalnika naj bo obleka dirkalnika, ki se bo lahko nanj hitro namestila in prav tako tudi hitro snela. Lahko jo bomo zamenjali enako, kakor človek zamenja obleko.

One of the most important properties of the racing car is defined by the wheel diameter. Therefore, this fact should also be based on investigating the competitors' cars. Contrary to the belief that the wheel diameter should be as small as possible in order to reduce weight, the first four teams were equipped with (rather large) 13" wheels. Larger wheels improve the drive properties of the racing car so effectively that the additional weight can be neglected. This was the most powerful argument that convinced the Formula S crew to continue with 13" wheels.

The most common belief is that the racing car should have a car body that is made of steel sheets or artificial materials rein forced by glass fibers, carbon fibers or aramid fibers. Only the car body gives the car its final shape. In our case the car body weighs from 15 to 25 kilograms, which is around 7 or more percent of the total weight of the car. For this reason this fact we decided to drastically reduce the car body mass by introducing a car body made of hardwearing cloth. The car body should be a cloth that can be fitted and removel quickly – just like an ordinary set of clothes.

3 SKLEP

Kakovost dirkalnega avtomobila je odvisna od dobro zasnovanih in narejenih podrobnih rešitev, kakor je v tem primeru predstavljen sesalni sistem, prav tako pa je kakovost odvisna tudi od dobrega osnovnega osnutka. V tem prispevku sta prikazana pomena obeh prijemov. Rešitve, ki sta jih prinesla analiza in optimiranje sesalnega sistema, so že uporabljene v najnovejšem modelu dirkalnika Formula S, medtem ko bodo prikazane zamiselne rešitve prišle v uporabo s prihodnjimi modeli. Glede osnutka dirkalnika Formula S pripravljamo v prihodnjem kar nekaj izrazitih sprememb, ki jih je težko ovrednotiti s številkami, a morajo pozitivno vplivati na značilnosti dirkalnika, ker so večinoma usmerjene v zmanjševanje geometrijskih izmer in mase dirkalnika. Zaradi finančnih razlogov ne bo mogoče prav vseh zamiselnih sprememb uporabiti na modelu naslednje sezone, vendar smo prepričani, da bo že vsaka sprememba pomagala tako v boju za nove točke glede inovativnosti, kakor tudi glede hitrosti in zmožnosti dirkalnika.

3 CONCLUSION

The racing car's characteristics depend on well-designed and well-made details, which in our case is illustrated by the optimized intake-manifold system. On the other hand, the car's quality depends even more on a good basic concept. In this paper the meaning of both approaches is pointed out. The solutions, which are the result of the analysis and the optimization of the intake manifold, are already in use in the latest model of the Formula S racing car. The conceptual solutions will be implemented in future models. For the near future, some even more drastic changes to the concept of the Formula S racing car are being prepared. These changes are very hard to evaluate numerically but they should all improve the dynamical properties of the vehicle because they are mostly related to the dimensions and reducing the mass. For economic reasons it will not be possible to implement all of the planned improvements to cars in the near future. However, we are convinced that each introduced change will help us in the battle for higher scores by giving us better general characteristics of the racing car, such as higher speeds.

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