CONCEPTUAL DESIGN BRAKE PAD: A STUDY TO APPLICATION ON REGENERATIVE BRAKING

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Abstract. *This work presents the development of the informational and conceptual design of a brake disc considering regenerative braking. The development of clean and higher efficiency vehicles depends on the analysis and optimization of the performance characteristics and driving conditions, mainly for urban vehicles. In this way is proposed the informational design that allows the identification of the specific user requirements for a brake system of a urban vehicles, whose unfold of user requirements allowed identify technical conflicts and the components involved with them. Using the analytical methods and numerical method as finite difference was investigate the behavior of some variables related to vehicle performance as: pad friction, coupling force and torque and dissipated energy as well as to estimate the temperature variation in the pad during the braking process.*

Keywords*: design methodology; brake pad; heat distribution; parameter's analysis; regenerative braking.*

NOMENCLATURE

A = area, mm^2
c = specific heat, $m^2/s^2.K$
E = energy, J, $kg.\ m^2/s^2$
f = friction, []
F = force, N
h = heat transfer coefficient, $W/m^2.K$
H = energy, W, $kg.\ m^2/s^2$
I = moment of inertia, $kg{\cdot}m^2$
k = thermal conductivity, $W/m.K$
m = mass, kg
p_a = absolute pressure, kPa
r = radius, mm
t = time, s
T = temperature, K, ^oC, ^oF
T = torque, $N.m$
U = energy rate dissipation, $N.m/s$, W, J
W = mass, lb_m
Δx = distance between nodes, mm
θ = angle, ^{o}
ω = angular velocity, rad/s

1. INTRODUCTION

The design of brake systems is an important topic in machine design and it is very important focus an automotive industry once that composed a safety item of a vehicle. The modifications of a basic design of a brake system it is very complicated due the high costs involved. Nowadays, new energy sources as electric and hybrid vehicles are forced the incorporate of new technologies and materials to brake configuration. With the growth of world population, and consequently the fleet of road vehicles, the study of the use of energy lost during braking process becomes an alternative to reduce pollution in large cities. There are numerous proposals for hybrid cars using electric and combustion systems combined, which is quite useful for reducing pollutants in the atmosphere and noise pollution in major urban centers, since electrical systems do not generate high noises and would be better used at low speeds (Souza and Dedini, 2009),. The purpose of this study is to estimate heat losses generated in the friction between the brake pads and the disc through. The informational design lead optimization by identifying the technical conflicts between the existing components in the brake system, making the development process faster and more efficient, generating brakes that best meet the needs of the user losing as little energy. In the Brazilian network transport, there is a predominance of the highway transport where 96.2% corresponds to passenger transport and 61.8% includes load transport. The highway network has fundamental role to supply chains and interactions between segments of business, also to promote the integration of different regions and states (Gobbi, 2010). Due the importance of the new technologies to obtain alternative energy applied to urban vehicles, the basic design of brake pad should be adequate to new configurations of the wheels and suspensions as well to supply interactions between the variables related to energy generation and dissipation that it is important to power management batteries considering hybrid and electrical vehicles. So, the objective of this work is applied design methodology techniques to brake system to list and identify critical items then to expand to a case study where it is used an open program implemented in this work to analysis the interactions between main parameters involved in braking process and to estimate the heating variation of the brake system during the braking process using the Simulated Annealing method.

2. REVIEW

2.1. Design Methodology

The process of design development involves multidimensional activities with different approach like as: labor psychology, methodological process and organizational view (Pahl *et al*, 2005). The design process acts as an union of cultural and technological activities through the knowledge in the areas of natural sciences, engineering, design, economy, marketing, psychology and politics (Pahl *et al*, 2005). According to Back (2008) "design" is a wide concept, but it must be integrated through all activities of product planning and design. These activities include, for example, market research, the product design, the manufacturing, use of the product, the maintenance and distribution plans and the defuse or disposal of the product. Pahl *et al*. (2005) emphasize the recent recognition of the importance of the design methodology or theory of design in the product conception, whether they are alternative, adaptive or innovative design have generated standards such as the VDI 2221 (1985) and guidelines suggest in ASME publications (1986). In these publications the ASME in Mechanical Engineering recommendations and guidelines were presented to the teaching and research in the area. In the technical literature, there are some propositions to the systematic approaches to the design activities or strategies to find solutions (Back, 2008; Baxter, 2000; Pahl *et al.* 2005; Shabin, 1988). These propositions present, in a general form, small variations in face of techniques in the solution of the problems, as well as the approach, sometimes more technical (Back, 2008 and Pahl *et al.* 2005), sometimes more organizational. With regards to each activity in the design process, there is an analysis process and the subsequent synthesis process based on techniques and methods that lead the stages of work and decision-making. As the design activities evolve, the flux of information, which is initially conceptual, becomes gradually numerical results.

2.2. QFD (Quality Function Development)

The concept of QFD was introduced in Japan in 1966 by Yoji Akao, as consequence of changes of the market against to the postwar and new demands, such as decrease of the product life cycle, emergence of new technologies making equipments and products more complex. QFD is a technique that should be used during the informational design (House of Quality), but can be improvement along other phases of the design development as: manufacturing, assembly, and reliability (Peixoto; Carpinetti, 1999). In the first matrix of QFD called "House of quality" are identified the customer´s necessities and wishes that are "translated" to technical characteristics to lead the design configuration and the critical points considering technical and market approaches. In the first matrix or "House of Quality" the lines corresponds to set of informal phrases that describes the requirements/necessities customer elaborated together marketing group. This information's are "translated" or unfolding to technical requirements. This matrix represents a kind of database that reflects customer needs to a specific period. Through of this first matrix can be possible the discussion, evaluation and prioritization of costumer requirements as well as to identify the technical characteristics more important related to customer necessities considering the teamwork as marketing, product engineering and maintenance. According to Cheng, *et al.* (1995) QFD can be defined as a systematic way to communicate information related to the quality and neatly explain work related to the improvement of quality with focus on qualitative quality and quality temporal (reliability) during product development cycle.

2.3. Hybrids vehicles

Hybrid vehicles incorporate to internal combustion engine, in this case called "primary power source", a second power source (normally a battery or electric engine). The objectives of hybrid drive train are to improve the drivability of a vehicle for example, to reduce the pollution levels mainly in urban areas, fuel economy, safety and comfort (Hofman, *et al.* 2005). The hybrid system allows brake recovery energy, downsizing the engine and design of power flows considering different mechanical, thermal and electrical configurations with alternative power sources. The process of kinetic energy recovery lost during the braking is an alternative to increase the autonomy of hybrid vehicles where part of this energy is re-used. In the internal combustion engine vehicles the kinetic energy is totally lost to environment. The plumbum batteries is a current alternative to store this energy, possessing a relatively low cost, high resistance to variations of temperature and high durability, but presents disadvantages as its high weight, delay to be charged, is quickly discharged, suffers a reduction in voltage (small but constant) during the use and may not be fully recharged so often, like the other types. Its best use is sporadic, since this type of battery is designed to be constantly charged and discharged eventually (type of batteries used in cars, charging with the motor running and discharges when starting the engine or the operation of devices with the vehicle off) (Monteiro, 2008).Researches with lithium ion-air batteries have been made to eliminate the cobalt. This procedure will allow the formation of lithium oxide that can store 5 to 10 times more energy that traditional lithium ion battery (Jeffries, 2010). There are many researches involving electric and hybrid vehicles with some success, as example, "Prius" (Toyota industry) that is totally electric. The use of fuel cell is an alternative in a next future because reduce the pollutant emissions once there are not carbon emissions.

2.4. Finite Difference Method

The numerical method "finite differences" consists in the generating of a mesh on the surface of two-dimensional study, where displacement Δx is equal to Δy. The condition of steady state was used in order to find the critical temperature after long periods of braking. According to Incropera and DeWitt (2002), the mesh is generated based on as illustrated in Fig. 1:

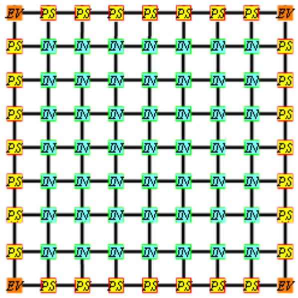

Figure 2. Mesh for Finite differences.

The internal nodes are obtained by eq. (1):

$$T_{m,n+1} + T_{m,n-1} + T_{m+1,n} + T_{m-1,n} - 4.T_{m,n} = 0 \tag{1}$$

Node on a flat surface with convection is given by eq. (2):

$$(2.T_{m-1,n} + T_{m,n+1} + T_{m,n-1}) + (2.h.\Delta x.T\infty/k) - 2.[(h.\Delta x/k) + 2].T_{m,n} = 0 \tag{2}$$

Nodes in a vertex with external convection are obtained (Eq. 3):

$$(T_{m,n-1} + T_{m-1,n}) + (2.h.\Delta x.T\infty/k) - 2.[(h.\Delta x/k) + 1].T_{m,n} = 0 \tag{3}$$

Where are generated the following equations:

$$\begin{matrix} a_{11}.T_1 + a_{12}.T_2 + a_{13}.T_3 + \cdots + a_{1N}.T_N = C_1 \\ a_{21}.T_1 + a_{22}.T_2 + a_{23}.T_3 + \cdots + a_{2N}.T_N = C_2 \\ \vdots \\ a_{N1}.T_1 + a_{N2}.T_2 + a_{N3}.T_3 + \cdots + a_{NN}.T_N = C_N \end{matrix} \tag{4}$$

$$A \equiv \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1N} \\ a_{21} & a_{22} & \dots & a_{2N} \\ \vdots & \vdots & & \vdots \\ a_{N1} & a_{N2} & \dots & a_{NN} \end{bmatrix}; \quad T \equiv \begin{bmatrix} T_1 \\ T_2 \\ \vdots \\ T_N \end{bmatrix}; \quad C \equiv \begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_N \end{bmatrix} \tag{5}$$

$$[T] = [A]^{-1}[C] \tag{6}$$

$$A^{-1} \equiv \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1N} \\ b_{21} & b_{22} & \dots & b_{2N} \\ \vdots & \vdots & & \vdots \\ b_{N1} & b_{N2} & \dots & b_{NN} \end{bmatrix} \tag{7}$$

$$\begin{matrix} b_{11}.C_1 + b_{12}.C_2 + b_{13}.C_3 + \cdots + b_{1N}.C_N = T_1 \\ b_{21}.C_1 + b_{22}.C_2 + b_{23}.C_3 + \cdots + b_{2N}.C_N = T_2 \\ \vdots \\ b_{N1}.C_1 + b_{N2}.C_2 + b_{N3}.C_3 + \cdots + b_{NN}.C_N = T_N \end{matrix} \tag{8}$$

In this numerical method it is possible to obtain the temperature at each node of the mesh generated which can outline the profile of the surface temperature in the point special interest.

3. CASE STUDY

Hybrid system for vehicles (urban or racing) allow the design of regenerative brakes which physical principle is the reuse of energy lost during the braking process that can be absorbed by vehicles batteries using an electric engine or hybrid propulsion. In the last years some design options have been developed including auxiliary modules assembled in the suspension and wheels of the vehicles considering easily as costs of installation, labor and minimum alterations in the original design. The mainly problem considering hybrid vehicles is the design space to assembly the batteries and regenerative brake system without to increase deliberately the weight and costs of the vehicle. To introduce the study of break system in hybrid vehicles it is necessary to obtain the workspace or free internal volume close to wheels. There are difficulties to find this information in the technical literature because the automotive industries develop its own studies and normally due to market competition do not make available these data. In this way, to develop this work it was made a "reverse engineering process" where from a commercial vehicle given by an automotive industry it were measured the brake system as well as the distances between the wheel and suspension and damper.

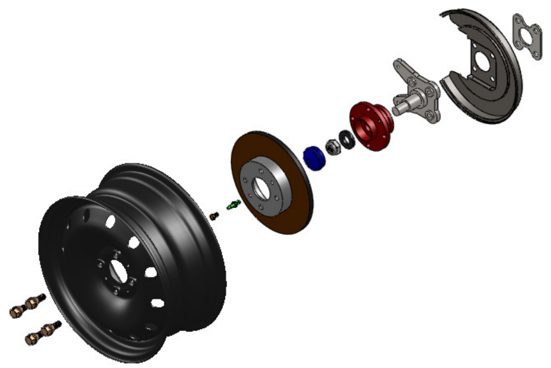

Figure 2 (a). Schematic model of wheel of a commercial vehicle.

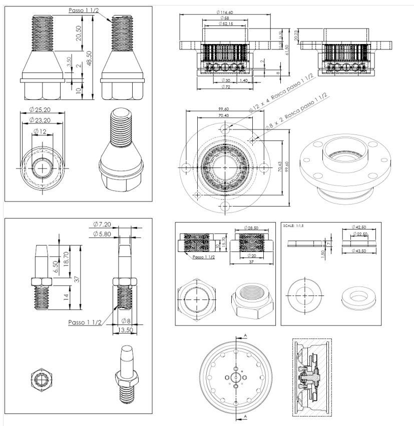

Figure 2 (b). Drawing of a brake system from physics model.

The Fig. 2 (a) presents the model generate from the physical wheel which allow to obtain mass properties and space available to brake system configuration and the Fig. 2 (b) presents the detailed drawings of the brake components.

4. PROPOSED METHODOLOGY FOR CONCEPTUAL DESIGN OF BRAKE SYSTEM

The design of brake systems involves the study of the parameters and variables to evaluate the coupling forces and torque, heat generated and dissipated, friction coefficient and geometries related to the contacts during the braking process. In a traditional braking system, brake pads produce friction through brake rotors to slow or stop the vehicle and an additional friction is produced between the slowed wheels and the contact area or surface of the road. The friction generates between pads and disk turn the car´s kinetic energy into heat. The brake pads have less braking capability than drum brakes, however this kind of brakes generate less heat that it is more easily dissipated into the air/environment. According to Kawaguchi (2005) the activate of the traditional vehicle brake system occur by pressing of the brake pedal which transmits the mechanical force to the whole brake booster/master cylinder that it was turned on hydraulic pressure activating the brake. New approaches to the storage of the energy generate during of the braking process have been proposed, but there no have a closed solution. Hybrid vehicles use conventional brake pads at highway speed while the electric motors are used to support the braking process of the vehicle during the process of stop and go driving. When the driver activates the brakes through of a conventional pedal, the electric motors reverse direction. The torque generate by this reversal counteracts the forward momentum and normally stops the vehicle. The idea is the use of regenerative brakes mainly applied to hybrid (Internal Combustion Engine (ICE)/Electric) vehicles is storage the kinetic energy involved during the braking using which approach includes: flywheels energy store, where the transfer of torque is made by transmission system (CVT) to flywheel, drive-wheel and road wheel. In this work is proposed the procedure for brake design system that includes: a) informational design is constructed a House of Quality (QFD) to translate the costumer necessity with technical solutions relate in a correlations matrix. This tool has two mainly functions in the design development process: it is a kind of databases that reflects characteristics of a "product" in a specific time and brings forward technical conflicts in function of the improvements and innovations. After that it was elaborated a partial functional analysis to identify the critical components considering the hybrid vehicles. This step corresponds to conceptual design. From these information was developed and implemented a program to study the relationship between the main parameters involved in the braking process as well as to find maximum/minimum values to functions related to temperature and operational parameters.

4.1 QFD - *Quality Function Deployment*

The Brainstorming technique was developed considering a sample of 10 drivers of urban vehicles with age in the range of 20-40 years old. It was considered a low cost car with average price of the U$ 16,200.00. From the Brainstorming information and research on technical literature was made the first matrix of the QFD methodology whose objective is traduce the user’s requirement to technical characteristics. Using this technique it is possible to anticipate technical conflicts from “roof “of the matrix and to identify the user´s requirements with great importance. These data were used to definition of users’ requirement and is presented in the Fig. 3.

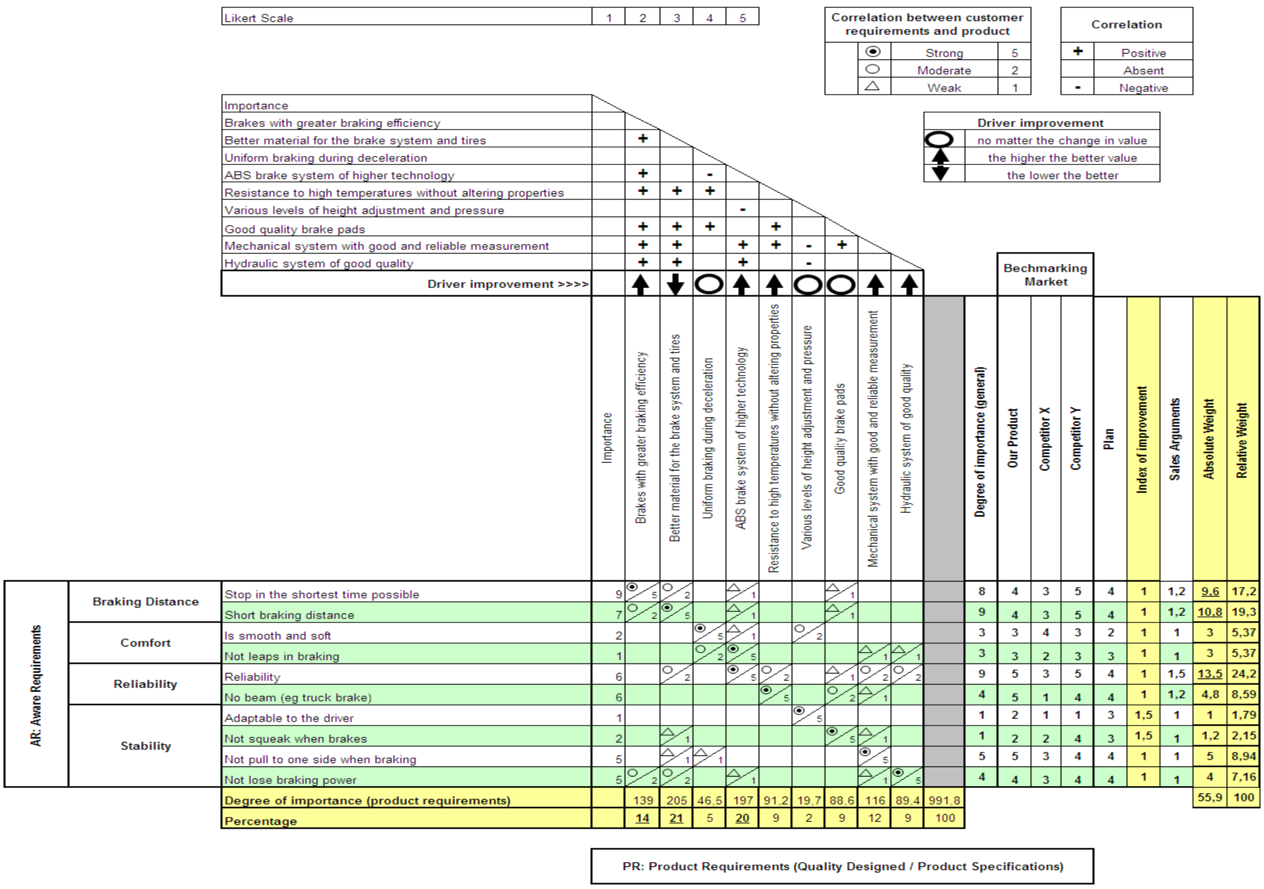

Figure 3. First house of QFD: “brake system to passenger car.”

Analyzing the matrix it was identified on user viewpoint three requirements with more importance: “Be reliable” (24%); “short breaking distance” (19%) and “Stop in the shortest time possible” (17%). These requirements were translated on technical viewpoint as: “better material for the brake system and tires” (21%); “higher technology to improvement of brake system” (20%) and “more efficiency during the braking process” (14%). In the “roof” of matrix were identifying four technical conflicts:

1. “Various levels of height adjustment” x “pressure efficient of the hydraulic system”;
2. “Various levels of height adjustment” x “reliability of the mechanical system”;
3. “Higher technology to improvement of brake system” x various levels of height adjustment and pressure”;
4. “Uniform braking during deceleration” x “higher technology to improvement of brake system”.

4.2 Functional diagram for brake system

The functional tree is an approach where the design functions (using the semantic construction: verb plus substantive) are joined with components and conversely. The focuses of this work is applied QFD (House quality) to the brake system and identify the components that are related to user and technical requirements (Pahl *et al*., 2005). So, was made simplified functional tree (Fig. 4), which were identified the main subsystems of a brake disc system.

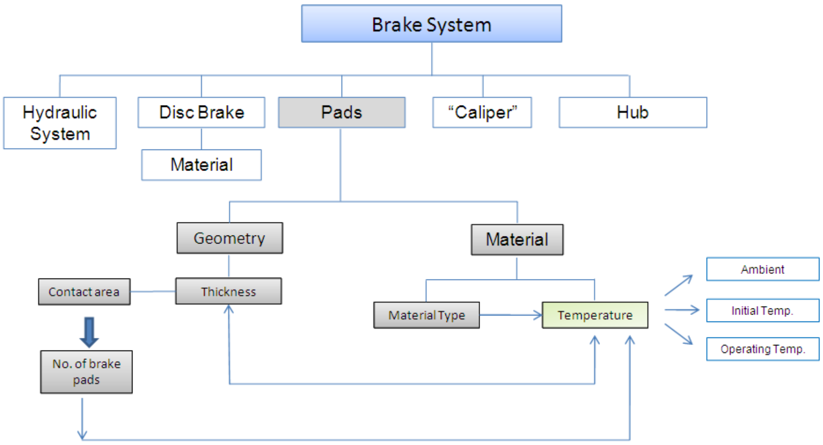

Figure 4. Functional analysis preliminary of brake pad.

Look at the main subsystem and considering the QFD indications the "pad subsystem" was unfolding to identify the relationship between design parameters and which parameters have more relationship with design functions. The use of functional tree to system "brake" can be involve a high level of complexity if it will be considered systems and subsystem related, for example to the dynamic behavior of the vehicle, modal analysis, reliability and durability estimative, endurance analysis and energy balance. In this work, the informational design was made considering only "component brake", but can be extend to other subsystems of the vehicle where must be considered the movements equations of the components that have influence on brake pad performance. From the House of quality - QFD for a brake pad for urban vehicle with less cost were identified the costumer characteristics with more relative weight: "better material for the brake system and tires" and "more efficiency during the braking process". These two characteristics are indicated in the functional tree as: pads unfold in geometry and material. The performance of brake system is related to potential and kinetic energy balance from different automotive components, for example, disc and tire-ground, during the dynamic and break conditions of vehicle and the heat transference involved between the material of the brake pad and disc. According to Hodel (2009) the failure modes in brake pads are related to premature wear due the misalignment during the assembly or/and choice inadequately of the material and the natural wear. The design function of the brake pad is "to provide friction" during the braking process of vehicle with safety and reliability during its useful life. These conditions lead to reduction of the efficiency to braking system. The loss of friction and the glassy process are elevation in the operational temperature contributing strongly to the reduction of the efficiency of brake. The design function of the disc is to "reduce the kinetic energy" of the wheels and its failure modes are: glassy and warp which cause is the high temperature during the brake process. This design procedure represent the informational design whose parameters and variables indentified will be evaluate using numerical methods.

4.3 Basic design for brake pad and energy balance

The design of brake pad as machine element considers two assumptions. The first assumption considers that a brake pad in the initial useful life does not present wear, hence the pressure is uniform on everywhere pad area with disc. So, during the operational condition the initial wear is higher in the outside radius (Shigley, 2005). The Fig. 5 presents a simplified geometry of the brake pad.

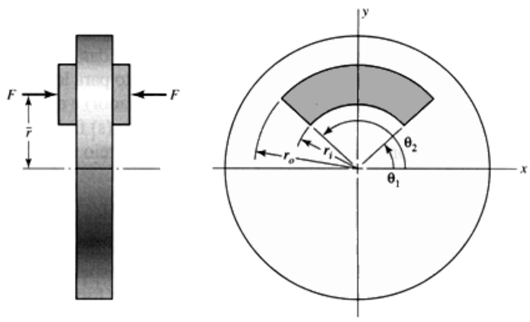

Figure 5 – Schematic view of brake pad (Shigley, 2005).

For this case (uniform pressure), the governing equations to obtain the force and torque coupling are given by equations (9) and (10):

$$T = \frac{1}{3}(\theta_2 - \theta_1) f\, p_a (r_o^3 - r_i^3) \tag{9}$$

$$F = \frac{1}{2}\,(\theta_2 - \theta_1) p_a (r_o^2 - r_i^2) \tag{10}$$

The other assumption considers the brake pad in operational conditions which there is a uniform wear and so, the relation pressure x speed must be constant. The higher pressure happens on the smaller radius (Shigley, 2005). In this case (uniform wear), the governing equations are given by equations (11) and (12):

$$T = \frac{1}{2}\,(\theta_2 - \theta_1) f\, p_a\, r_i\, (r_o^2 - r_i^2) \tag{11}$$

$$F = (\theta_2 - \theta_1) p_a\, r_i\, (r_o - r_i) \tag{12}$$

The change of the velocity in a system implies in the energy balance. During the braking the kinetic energy from rotation must be absorbed by brake that will be converted in heat and dissipated to the environment. The temperature in brakes became critical when the heat generate is higher than its dissipation that generate the excessive heating in the components of the brake system. The dissipation rate energy during the braking is influenced by torque and the time of application of this in the brake system given by equation (13):

$$U = T \cdot \left(\omega_1 - \frac{T}{I_1} \cdot t\right) \tag{13}$$

The integration of dissipation rate energy supplies the total energy dissipated during the braking of the vehicle through the equation (14):

$$E = \frac{\omega_1^2 \cdot I_1}{2} \tag{14}$$

The time used until total braking of wheel will be given by equation (15):

$$t_1 = \frac{\omega_1 \cdot I_1}{T} \tag{15}$$

The instantaneous input of heat in the brake q is equal to the change of kinetic energy in the vehicle:

$$q = \frac{\partial}{\partial t}\left(\frac{1}{2} \cdot m \cdot v^2\right) \tag{16}$$

The design of the brake system will determine the percentage of total heat that will dissipate at each wheel. Predicting temperatures of brake systems is extremely difficult in operational conditions because they are operated widely varying conditions. Considering the first law of thermodynamics to balance of the energy input into brake system from friction between sliding elements and simplified the equations where conduction and convection are negligible, the instantaneous temperature rise in the brake material can be approximated by equation (17):

$$\Delta T = \frac{H}{c \cdot W}, \qquad \Delta T = \frac{E}{c \cdot m} \tag{17}$$

English System — International System

The equations 13, 14, 15, 16 and 17 present the energy dissipation generate during the braking process. The cooling for the brake system can be simplified by equation (18):

$$T_i - T_a = (T_1 - T_a) \cdot e^{-\left(\frac{AU}{WC}\right) \cdot t} \tag{18}$$

5. RESULTS

From the data obtained QFD and functional analysis can be concluded that the temperature is a critical parameter related inclusive with reliability of the vehicle besides the safety that is clear on overview of vehicle commercial. Considering the hybrid vehicles the thermal energy generates must be minimized because in this form the energy cannot re-used in hybrid engineer. To obtain the generate torque; the normal force applied on the brake disc must be known as well as the friction between the materials and the area where the force is applied. These values are obtained from the equations (9) and (10) or (11) and (12) depending of hypothesis adopted this means that the both hypothesis are used in braking systems: in the start of brake operations and during the useful life. The normal pressure is results of normal time's actuation area of force as shows by Fig. 6 considering both assumptions and presents a linear relationship.

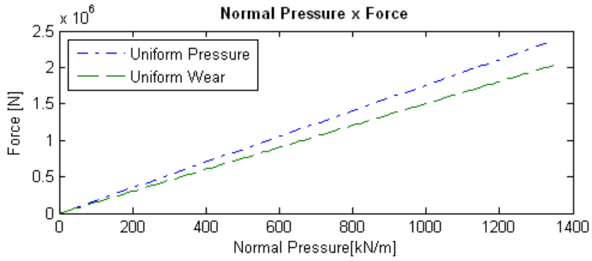

Figure 6. Normal Pressure x Force applied.

From the maximum pressure find in the function found in the graphics of the Fig. 6, it is possible to estimate the applied torque in the pad brake during the braking process and with this to obtain the maximum capacity of the torque generation to the system. The Fig. 7 presents the range of available torques considering the variation of normal pressure and the friction to the two conditions of the work of the pads.

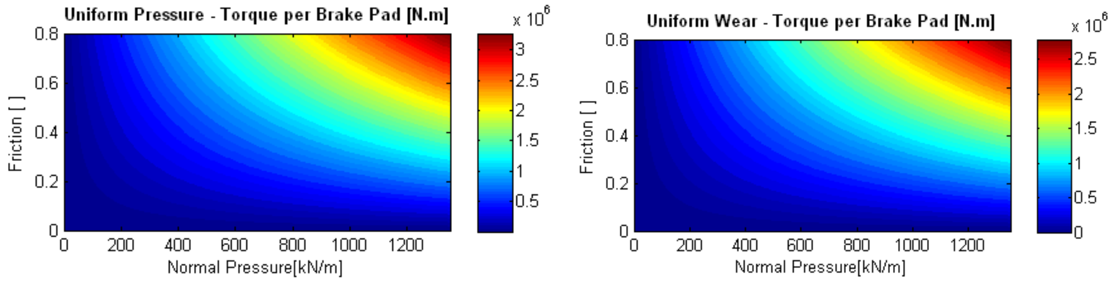

Figure 7. Generate torque in the pads brake.

With the maximum torque that can be generate in the brake disc it is possible calculated the energy quantity generate in the heat form to environment considering the actuation time in the brakes using the eq. (13). The Fig. 8(a) presents the dissipation rate energy sent to air. From the eq. (15) it is possible to observe that the generate torque has direct influence in the stop time of the vehicle presented in the Fig. 8 (b). In this way it is possible to obtain the optimum torque where the lost energy is the minimum (in these constraints) maintaining a stop time allowed.

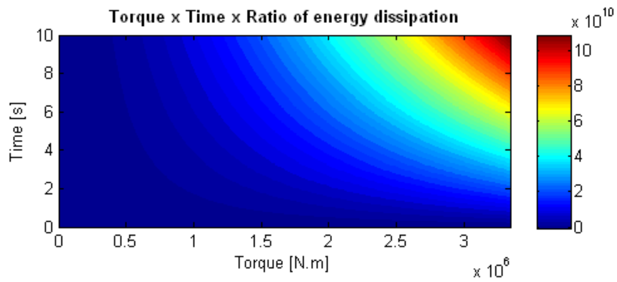

Figura 8(a). Distribution of lost energy (Isocurves).

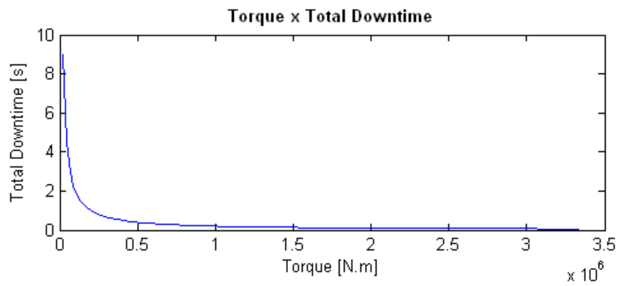

Figure 8 (b). Torque x Total Downtime.

With the torque estimate and dissipated energy can make an optimization of area of pad brake with the objective to minimize the thermal energy loss and to maximize the torque generate during the braking of the vehicle. The choice of the material for brake is important criterion because the friction generated depends directly of the material properties and the surface temperature of contact between pad/disc leading the problem of the heating of brake. The instantaneous heat input in the brake can be approximated by eq. (16) being equal to variation of the kinetic energy of the vehicle divided by number of brakes in the vehicle. The Fig. 9 presents the input heat of the brake system.

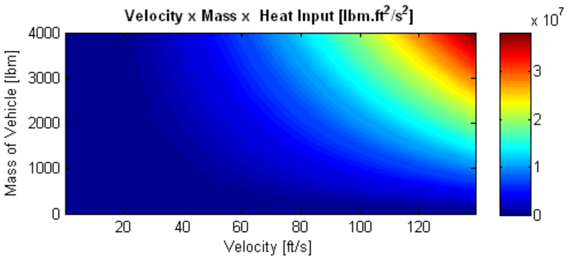

Figure 9. Input heat.

The design of the brake system will determine the percentage of the total heat generated that it will be dissipate in each wheel. The increase of the temperature in the brake design can be approximated by eq. (17) presents by Figure 10.

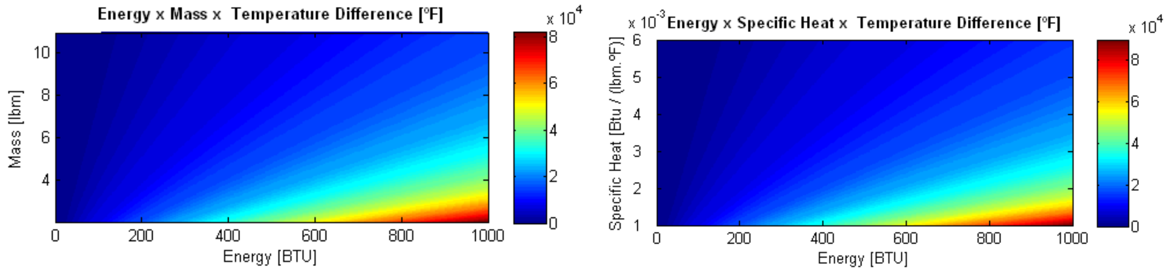

Figure 10. Temperature Gradient.

The results obtained presents on the graphics and the eq. (17) analyzing the brake operation and must be made to many cycles to improve the evaluation of the main parameters of the brake system. The Fig. 11 presents the cooling of the brake system obtained from eq. (18).

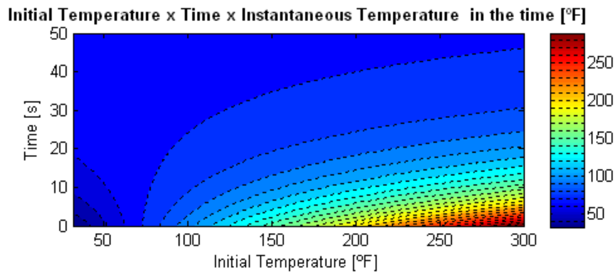

Figure 11. Instantaneous Temperature.

An important point that must be observed is the residual torque, which does not increase the operational temperature. This condition reduces heat loss in the brake system, changing a lot the temperature equilibrium after many brakes.

The distribution inside the brake pad as showed in the Fig. 13, can be estimated using the numerical method of the finite differences. For initial study of the heat distribution of the pad it was made a simplified model – 2D, presents by Fig. 12, as lateral section in the brake pad.

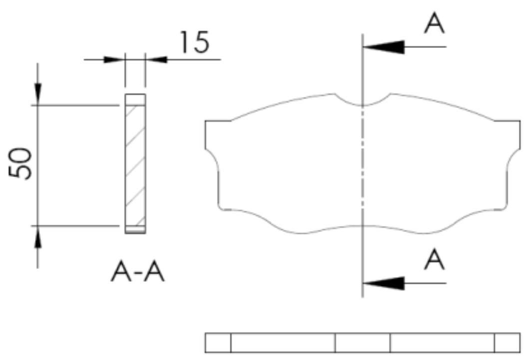

Figure 12 - Section of a brake pad.

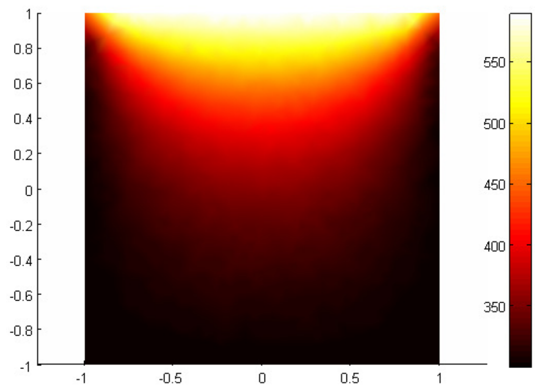

Figure 13. Temperature gradient on brake pad.

6. CONCLUSIONS

There are many energy losses in thermal way to environment in a vehicle during each process braking. Considering hybrid vehicles kinetic energy can be stored in the batteries to be used latter to aid the propulsion of the vehicle. The informational and conceptual design lead to systematic approach to design of the brake systems. In this way, the first solution from the study presented in this work is optimize the brake shapes with objective to improve the efficiency of the mechanism with less thermal energy loss and consequently a efficient braking with less wear of the pad. The option by design of electric system brakes can to create an opposite torque to movement with regenerating of the loss energy during the process braking. The recovery energy could be management by an intelligent network to distribution of the energy back to electric motors. The temperature distribution inside the brake pad can help to identify critical points of temperature and in this way to improve the pad material or layers of material adequate to each critical region. The quantification of the lost energy in commercial brake systems is the first step to improvement and fitting these to hybrid vehicles provided the lost energy is the same for electric brakes or friction brakes because depends on the kinetic energy of the vehicle and to capacity of the regenerative system.

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