KAUNAS UNIVERSITY OF TECHNOLOGY
MECHANICAL ENGINEERING AND DESIGN FACULTY

Daivaras Simanavičius

ANALYSIS OF THE ENDURANCE OF AUTOMOTIVE TIMING BELTS TO TENSILE FORCE

Master's Degree Final Project

Supervisor
Assoc. prof. dr. Robertas Mikalauskas

KAUNAS, 2016

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Reviewer
Assoc. prof. dr. Kazimieras Petkevičius

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KAUNAS, 2016

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"Analysis of the endurance of automotive timing belts to tensile force "

DECLARATION OF ACADEMIC INTEGRITY

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Kaunas

I confirm that the final project of mine, **Daivaras Simanavičius**, on the subject "Analysis of the endurance of automotive timing belts to tensile force" is written completely by myself; all the provided data and research results are correct and have been obtained honestly. None of the parts of this thesis have been plagiarized from any printed, Internet-based or otherwise recorded sources; all direct and indirect quotations from external resources are indicated in the list of references. No monetary funds (unless required by law) have been paid to anyone for any contribution to this thesis.

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Head of Production engineering Department

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MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme INDUSTRIAL ENGINEERING AND MANAGEMENT

The final project of Master studies to gain the master qualification degree, is research or applied type project, for completion and defence of which 30 credits are assigned. The final project of the student must demonstrate the deepened and enlarged knowledge acquired in the main studies, also gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Master studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

Analysis of the endurance of automotive timing belts to tensile force

Approved by the Dean Order No.V25-11-7, 3 May 2016

2. Aim of the project

Research for the automotive timing belt endurance dependences

3. Structure of the project

Introduction: problem, aim, and importance.
Literature analysis: literature analysis related to automotive timing belts, theory of synchronous drive systems, statistical methods.
Methodology: research objects characteristics, testing equipment.
Research part: data review, timing belt dependences from tensile force, price, origin country and brand statistical analysis.
Results and recommendations: project and research review and conclusions .

4. Requirements and conditions

5. This task assignment is an integral part of the final project

6. Project submission deadline: 2016 May 20.

Given to the student: Daivaras Simanavičius

Task Assignment received: Daivaras Simanavičius

Supervisor: Assoc. prof. dr. Robertas Mikalauskas

Daivaras Simanavičius. Automobilinių paskirstymo diržų atsparumo tempimo jėgai analizė. *Magistro* baigiamasis projektas / vadovas doc. dr. Robertas Mikalauskas; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis: Gamybos inžinerija, Technologijos mokslai.

Reikšminiai žodžiai: *automobiliniai paskirstymo diržai, diržinės sistemos, patvarumo testas, paskirstymo diržo priklausomumas nuo faktorių, diržų tempimo jėga*

Kaunas, 2016. 45 p.

SANTRAUKA

Šiais laikais automobiliuose plačiai naudojami paskirstymo diržai. Jie yra vieni esminių elementų norint užtikrinti sklandų vidaus degimo variklio darbą. Rinkoje yra nemažai įvairių gamintojų, vieni jų jau seniai daugumai žinomi, kiti – nauji gamintojai dar nespėję užsitarnauti savo vardo. Paskirstymo diržų kainos skirtingos, pagaminimo šalys labai įvairios, taigi yra sunku nuspręsti kuris paskirstymo diržas yra geresnis ir nuo ko priklauso jo ilgaamžiškumas. Tam išsiaiškinti buvo surinkti įvairių gamintojų gaminiai montuojami C9DA variklyje. Pagaminus testavimo įrenginį (variklio C9DA imitaciją) buvo išmatuota ties kokia įtampos jėga paskirstymo diržas nutrūkdavo. Surinkus informaciją: paskirstymo diržo įtampos jėga nutrūkimo metu, gamintojų pavadinimai, kilmės šalys ir vidutinės kainos rinkoje, buvo atlikta statistinė analizė su SPSS programiniu paketu. Statistinei analizei pasitelktas tiesinės daugialypės regresijos metodas. Atlikus statistinę analizę, jos tinkamumo kriterijai parodė jog pasirinktas statistinis modelis tinka mūsų duomenims ir tyrimui. Gautas determinacijos koeficientas yra beveik 0.7 o tai reiškia, kad mūsų modelis teisingai paaiškina beveik 70 procentų duomenų. Tyrimas atskleidė, kad norint įsigyti patvarų paskirstymo diržą vien kaina remtis nereikėtų, nes ir vidutinės rinkos kainos paskirstymo diržai nedaug atsilieka savo patvarumu nuo brangesnių paskirstymo diržų. Pigūs paskirstymo diržai stipriai atsilieka savo patvarumu nuo konkurentų, taigi jų pasirinkimas labai abejotinas. Statistinės analizės metodu gautas atsparumo įtampos jėgai koeficientas yra 0.592, o tai reiškia, kad atsparumui įtampos jėgai padidėjus 1.35 Nm (1 lbs.) paskirstymo diržo kaina padidėja 0.59 euro. Pagal kitus kriterijus matyti jog geriausi paskirstymo diržai yra gaminami Europos šalyse ir mažesni, nauji gamintojai turi pasitemti kokybės klausimais, nes vien kaina įeiti į rinką bus sunku.

Daivaras Simanavičius. Analysis of the endurance of automotive timing belts to tensile force thesis in industrial engineering and management / supervisor assoc. prof. Robertas Mikalauskas. The Faculty of mechanical engineering and design, Kaunas University of Technology.

Study area and field: Production and Manufacturing Engineering, Technological Sciences

Key words: *automotive timing belts, synchronous drive systems, endurance test, timing belt dependences, belt deflection force*

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SUMMARY

Nowadays in automotive world timing belts are used widely. Timing belt is one of the most important part of combustion engine. Now on the market there are quite a lot of manufacturers, some of them are old and well known, others – just are new and try to find their place on the market. Timing belts prices, origin countries, brand names are very different and it is hard to make a decision which timing belt characteristic is the main for the timing belt endurance. To figure out this, we have collected few manufacturers' products for C9DA engine. After a testing bench (imitation of the C9DA engine) was made we have measured the endurance of the belt by applying the deflection force till the belt failed. The data was collected: deflection force when belt failed, origin country, brand names, average price on the market. The statistical analysis was made by the help of statistical package SPSS. The multiple linear regression statistical method was chosen for the research. After statistical analysis we found that the chosen statistical method is good for our data, because the model fit parameters were all good. The determination coefficient R^2 was around 0.7, this means that our model explains ~70 proc. of data. Analysis have shown that if you want to get timing belt with more endurance you shouldn't pay attention only to price, because the timing belts with the average price is almost equal at the endurance test. The cheap ones is not a match at the endurance to their more expensive competitors, so the chosen of them is questionable. Statistical analysis also showed that our deflection force when belt failed coefficient is 0.592 and this means that endurance in deflection force increase by 1.35 Nm (1 lbs.) timing belt price increases by 0.59 euro. If we look to the other characteristics we can see that the best timing belts is made in European countries and a smaller, new manufacturers has to increase their technologies, because going in to the market by the price is not always an option.

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INTRODUCTION

In the automotive and industrial world the synchronous drive systems are very important, because of their ability to transfer the rotary movements. The main object of that system is a specially designed and made belt. This system is most widely used in automotive world. It helps to transfer movements of the engine accessories. The most important application is the timing system of the engine, because the failure in this system can do quite a big financial damage to manufacturer or owner of the vehicle.

Nowadays there is a huge market of the timing belts manufacturers. Some of them are widely known others are new and just try to put themselves in to the market. The prices of the timing belts are also very different, so it is hard to know which of them the best choice is. Different manufacturers use different technologies and materials for fabrication. So it is hard for customer to choose the best variant according to belt endurance and price. So in this paper we will try to do timing belt endurance to tensile force dependence from price on the market, brand and origin country analysis. The endurance of the belt will be decided by increasing deflection force till timing belt failure occurs. This item is chosen because everyone wants to get the best product they can and want to know what that best choice is and to which characteristics the most important for their decision is.

There exist some analysis [8][9] of the timing belts markets and industries, other papers checks the resistance of the environment impact to timing belt, it is hard to find something similar.

The aim of this research project is to find the endurance dependencies of timing belt from the average price on the market, origin country and brand.

1. ANALYTICAL PART

1.1 LITERATURE REVIEW

1.1.1 Timing belts history

Timing belt is quite young drive mechanism part. At first the idea of timing belt was belt with simple metal clips. It was used in sewing machines. The example of the timing belt origin is shown below in the Figure 1.1.1.

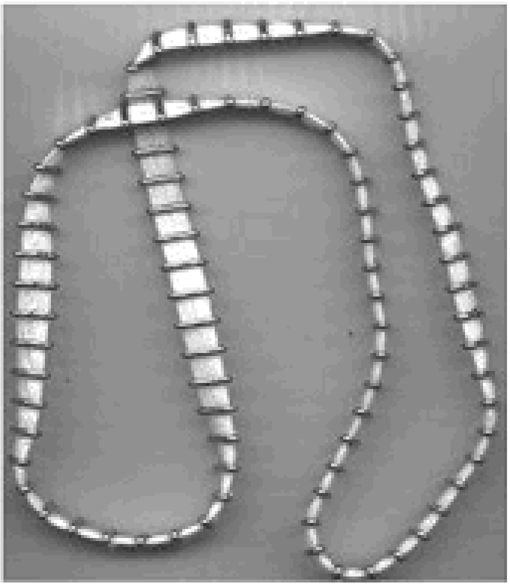

Figure 1.1.1 First timing belt concept

Timing belt which is a concept of belts used nowadays was designed in 1945 by Richard Case. It was a rubber belt with trapezoidal “teeth” profile. Its purpose was to transfer rotary movement of sewing machine. For the synchronization of needle and bobbin drives of sewing machines, belts with metal clips were used to replace the quite expensive and technically demanding bevel gear drives.

The problem of first timing belt was quite noisy operation. The problem was that trapezoidal metal clips on belt caused too much noise when turning metal toothed pulleys. Plus it caused some vibrations on sewing machine.

The first sewing machine with trapezoidal tooth profile was Singer A33. The sewing machine is shown in a Figure 1.1.2.

Figure 1.1.2 First machine used rubber timing belt (Singer A33)

The belt was made from chloroprene rubber and the technology was patented by Unites States company Uniroyal, which nowadays is more known as Gates in drive belts world. After this innovation other industries started to use and create timing belts across the world.

1.1.2 Timing belts in automotive industry

At the beginning of automotive industry rotary movement in combustion engines was transferred by timing chains or pulleys system.

Timing chains had these problems: more expensive to make, much nosier, lubrication was necessary. Pulley system had the biggest problem of engineering and correct timing alignment and was really expensive to manufacture compare to timing chain

In automotive world first car to be introduced with timing belt was a racing car build by Bill Devin in 1950s. The first mass production car was GLAS –Coupe S1004. How it looked is shown below in Figure 1.1.3.

Figure 1.1.3 GLAS-Coupe S1004

It was introduced in 1961 in Frankfurt's International Auto Show, Germany. The timing belt was called "Contilan" and made by the company which is well known today – Continental. Belt was made from special heat resistant polyurethane.

1.2 RESEARCH PLAN

The point of this work is to figure out how the endurance of timing belt (resistance to tension) depends from origin country, manufacturer and price of the timing belt. To achieve this point these task must be made:

- To do a theory analysis of the timing belt system;
- To build a testing bench;
- To collect required data;
- To do statistical analysis of timing belt endurance dependency from its average price on the market;
- To do a conclusion of the research.

1.3 TIMING BELT THEORY

Traditional understanding of timing belt drive systems is born from power transmission application. To make it simpler we are going to use just two pulleys in our system.

1.3.1 Geometry of timing belt

Timing belt pitch is the distance between two near teeth. Mostly it is measured from the belt pitch line (p), sometimes it is measured from the corner of one teeth to the other teeth (t). The schematic picture is shown below in Figure 1.3.1. Other important measurements are the diameters of belt or pulley pitches. (d)

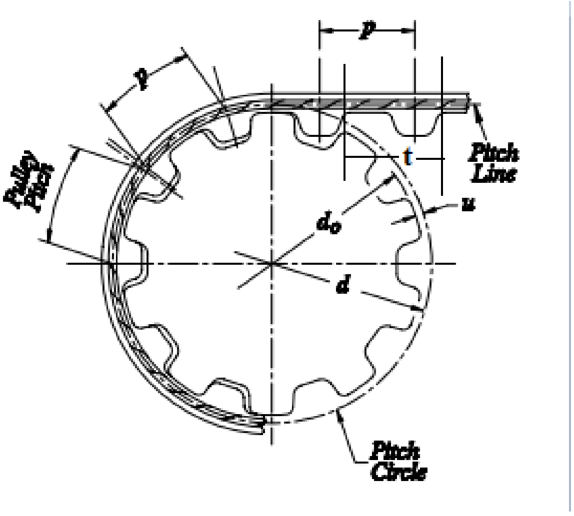

Figure 1.3.1 Belt on the pulley [1]

The pitch diameter and pulley outer diameter radial distance is named pitch differential (u). The belts are sorted to some groups. So called T-series, HTD-series and STD-series (S-series) belts are created to ride in the top lands of pulley teeth. AT-series type belts are designed to operate by the touch the bottom line of a pulley. The schematic difference is shown below in Figure 1.3.2.

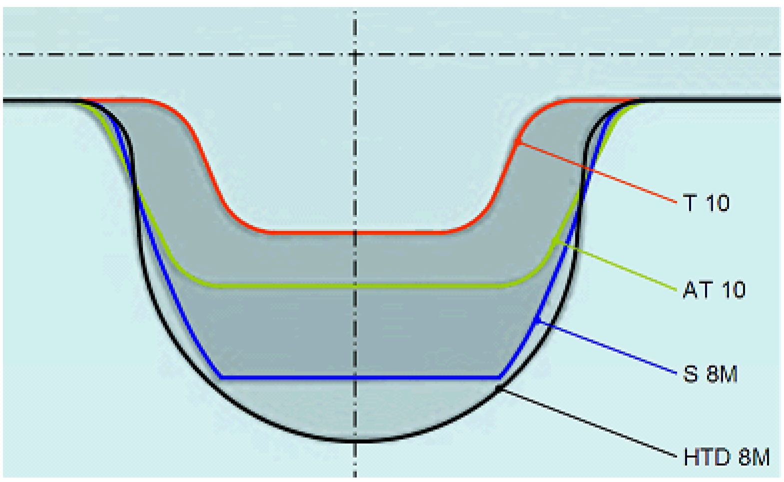

Figure 1.3.2 Differences between belt design series.

1.3.2 Timing belt structure

Main structure – cords:

Belt structure developed over the years. Nowadays structure depends from technical characteristics required. Most of them consist of basic elements.

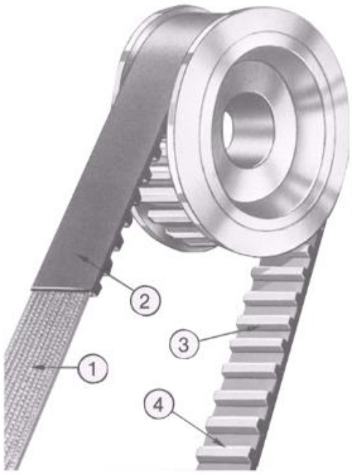

Figure 1.3.3 Belt structure scheme

1. Inextensible twisted cords;
2. Soft an flexible backing in polychloroprene;
3. Teeth made with synthetic rubber;
4. Nylon fabric with high resistance to wear.

These are common used materials; they can differ depending from the design and the manufacturer technology.

Some other materials used for manufacturing:

1. Polyester:

The advantages of polyester cords over higher tensile cords are the lower modulus of polyester, enabling the belt to rotate smoothly over small diameter pulleys. Moreover it helps to absorb shocks.

Table 1.3.1 Belt made from polyester spec.

Tensile Strength	11246 kg/cm^2
Elongation at break	14%

2. Kevlar:

Belts with Kevlar have specific strength and low elongation. This material is expensive but very good for manufacturing. Timing belt has excellent shock resistance and it is capable to survive high loads.

Table 1.3.2 Belt made from Kevlar spec.

Tensile Strength	28123 kg/cm^2
Elongation at break	2.5%

3. Fiberglass:

The advantages of fiberglass are: high strength, low elongation, dimensional stability, chemical resistance, temperature resistance. The opposite sides are difficult to bend, brittleness of glass, bad shock absorbing.

Table 1.3.3 Belt made from fiberglass spec.

Tensile Strength	24607 kg/cm^2
Elongation at break	2.5-3.5%

The table of comparison in specific requirements for timing belts and main materials used is shown below in Table 1.3.4.

Table 1.3.4 Materials used in belts comparison. [3] E – Excellent, G – Good, F – Fair, P – Poor

Belt Requirements	Nylon	Polyester Cont.Fil. Yam	Polyester Spun Yam	Kevlar-Polyester Mix	Kevlar Cont.Fil. Yam	Kevlar Spun Yam	Glass	Stainless Steel	Polyester Film Reinforcement
Operate over Small Pulley	E	G	E	F	P	F	P	P	G
High Pulley Speed	E	E	E	F	P	F	P	P	G
High Intermittent Shock Loading	F	G	G	E	E	E	P	G	F
Vibration Absorption	E	G	E	G	F	F	P	P	F
High Torque Low Speed	P	P	P	F	G	F	E	E	F
Low Belt Stretch	P	P	P	P	G	F	E	E	G
Dimensional Stability	P	P	P	F	G	G	E	E	G
High Temperature 200° F	P	P	P	P	E	E	E	E	F
Low Temperature	F	G	G	G	G	E	E	E	G
Good Belt Tracking	E	G	E	G	F	G	F	P	E
Rapid Start/Stop Operation	F	G	E	G	P	G	P	E	G
Close Center-Distance Tolerance	P	P	P	P	G	F	E	E	G
Elasticity Required in Belt	E	G	E	G	P	P	P	P	P

Table 1.3.5 Characteristic of body materials [3]

Common Name	Natural Rubber	Neoprene	Urethane, Polyurethane
Chemical Definition	Polyisoprene	Polychloroprene	Polyester/Polyether Urethane
Durometer Range (Shore A)	20 – 100	20 – 95	35 – 100
Tensile Range (p.s.i.)	500 – 3500	500 – 3000	500 – 6000
Elongation (Max. %)	700	600	750
Compression Set	Excellent	Good	Poor
Resilience – Rebound	Excellent	Excellent	Good
Abrasion Resistance	Excellent	Excellent	Excellent
Tear Resistance	Excellent	Good	Excellent
Solvent Resistance	Poor	Fair	Poor
Oil Resistance	Poor	Fair	Good
Low Temperature Usage (°F)	–20° to –60°	+10° to –50°	–10° to –30°
High Temperature Usage (°F)	to 175°	to 185°	to 175°
Aging Weather – Sunlight	Poor	Good	Excellent
Adhesion to Metals	Excellent	Good to Excellent	Fair to Good

1.3.3 Timing belt failure types

Common causes of belt failure:

- Normal belt wear

  When belt reaches its maximum tensile cord wear. It can be reached by two basic factors: lifespan time and running mileage.

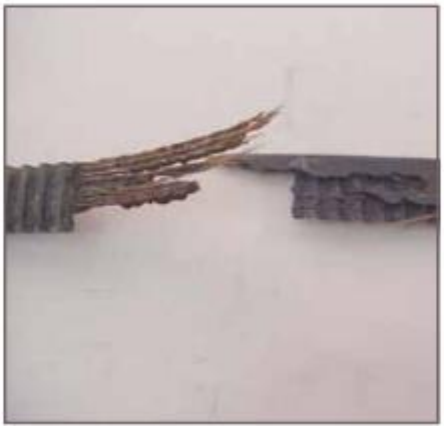

Figure 1.3.4 Normal belt failure example

- Belt crimp failure

  This type of failure occurs when straight tensile failure appears. It could occur when belt tensile cords is bended around small diameter. Belt crimping failure is mostly because of: belt mishandling, wrong installation (tension), sub-minimal pulley diameter or some inappropriate objects entered drive belt system.

Figure 1.3.5 Crimp failure example

- Shock load failure

  When in belt driving system occurs higher than normal intermittent or cyclic torque load shock loading failure is plausible. Severe shock loads can result in belt tensile breaks with a ragged and uneven appearance.

Figure 1.3.6 Shock load failure example

- High belt tension

  Applying excessive installation tension to a synchronous belt may result in belt tooth shear or even a tensile break. Many belts that have been excessively tensioned show visible signs that sprockets have worn the belt land areas.

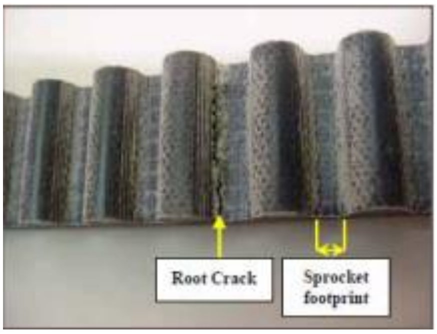

Figure 1.3.7 High belt tension problem

- Low belt tension

Too low belt tension can occur premature failures of bets. A common belt failure mode resulting from insufficient belt installation tension is referred as tooth rotation. Belt tooth rotation can occur as belt teeth climb out of their respective sprocket grooves and drive loads are no longer applied at their roots. Drive loads applied further down the belt tooth flanks cause the belt teeth to bend (like a diving board) and “rotate.” Belt tooth rotation can result in rubber tearing at the base of the belt teeth along the tensile member. As rubber tearing propagates, belt teeth often begin to separate from the belt body in strips.

Figure 1.3.8 Low belt tension example

- Pulleys misalignment

In the case of pulleys misalignment you are able to notice unequal wear of belt in sides of it. Uneven wear of belt tooth is quite plausible too.

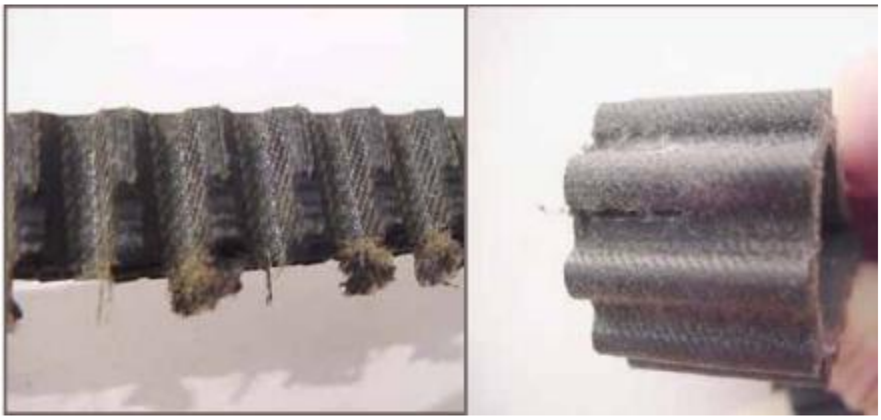

Figure 1.3.9 Pulley misalignment and unequal wear

- Too high temperature

Since the one of belts build materials is rubber, heat influence is critical for belt lifespan and wear. When rubber operates in high temperatures (greater than 87° C) for long periods, the rubber compound hardens and as result of that belt cracks in bending locations.

Figure 1.3.10 Timing belt reaction to high temperature

1.4 OPERATION OF BELT DRIVE

1.4.1 Low speed operation

The drive belt is well applied for slow and high torque application. The synchronous drives with small pitches usually operate at 25 centimeters per second or less is recognized as low speed operational. In this system stall and peak torques can be significantly high. Because of that belt tension is very important for preventing plausible belt jump when the torque loads.

1.4.2 High speed operation

In high speed timing belts are often used despite the fact that serpentine type belts are more suited for high speed. Synchronous belt drives are used because they are not slippery has no creep and they have almost no stretch. The main drawback of timing belt system in high speed synchronous drive is the noise. The synchronous drives with small pitches usually operate up to 6.5 meters per second is recognized as high speed operational system.

For design the focus should be held on a lot of factors. Belt tooth weariness and cord fatigue are the most important for high speed operational system. Because of cord flex fatigue the pulley diameters should be medium length. Smaller pitch length for belt ensures better cord flex fatigue and better belt tooth and pulley specifications of belt entering and leaving the pulley. In that case we are getting better wear and noise characteristics.

1.4.3 Timing belt appropriate operation

Some systems require that belt operation would have as less vibrations as plausible. Such system design mostly is done with some compromises; it is needed to sacrifice some specifications to increase the others. Vibration for belt drive operation is not considered as a case of death problem. Some lower vibrations mostly are an effect of tooth meshing process or high belt tension. Vibration as a result of belt operation is implausible to be reduced to 100 percent. Small pulley diameters are bad for this characteristic; if we want to make synchronous belt drive system with lower vibrations we should use medium or bigger diameter pulleys.

1.4.4. Operation environment

Timing belt is widely used in very many environments. This must be considered when designing the belt.

- Dusty environment is not a huge problem for the timing belt operation. The dust particles have no big harm for the system until they are not too big. The dust particles would work as an abrasive and at the end of that the timing belt system component will wear more quickly. Dust also can increase static charges and take affect bearings.
- Debris impact for synchronous drive belt system is huge. It can get stuck in the drive system and as the result of that it can end in whole system failure.

- Some water integration to drive belt system shouldn't do a lot of harm, but long contact with water decreases tensile strength and potential length variation in some belt types. Longer water impact makes rubber to swell. Other system components are more likely to be affected, like pulleys are mostly made from metal. They start to get rusty and it increases the friction between components and causes the quicker weariness or entire system failure. Water access to the bearings can cause their failure which leads to system broke down.
- Oil and other chemicals interference on drives system is more likely than it looks like. The oil interference in timing belt system is mostly seen in automotive world. Oil makes belt more slippery and it is more likely to jump over the pulleys tooth despite the fact that the tension of belt is normal. Oil as water causes swelling of rubber just oil has bigger effect than water. Other chemicals can do a lot of damage, in some cases entire system failure. How to prevent or protect the belt from which chemical affect should be discussed separately considered each chemical reaction results.
- Temperature is very important also. In low or very high temperature belt loses his flexibility and strength because of belt components characteristics answer to temperature.

1.5 PHYSICS OF SYNCHRONOUS DRIVE SYSTEM

1.5.1 Forces in timing belt drive systems

A timing belt transmits torque and motion from a driving to a driven pulley of a power transmission drive. In operation of belt drive under load a difference in belt tensions on the entering (tight) and leaving (slack) sides of the driver pulley is developed. It is called effective tension T_e and represents the force transmitted from the driver pulley to the belt.

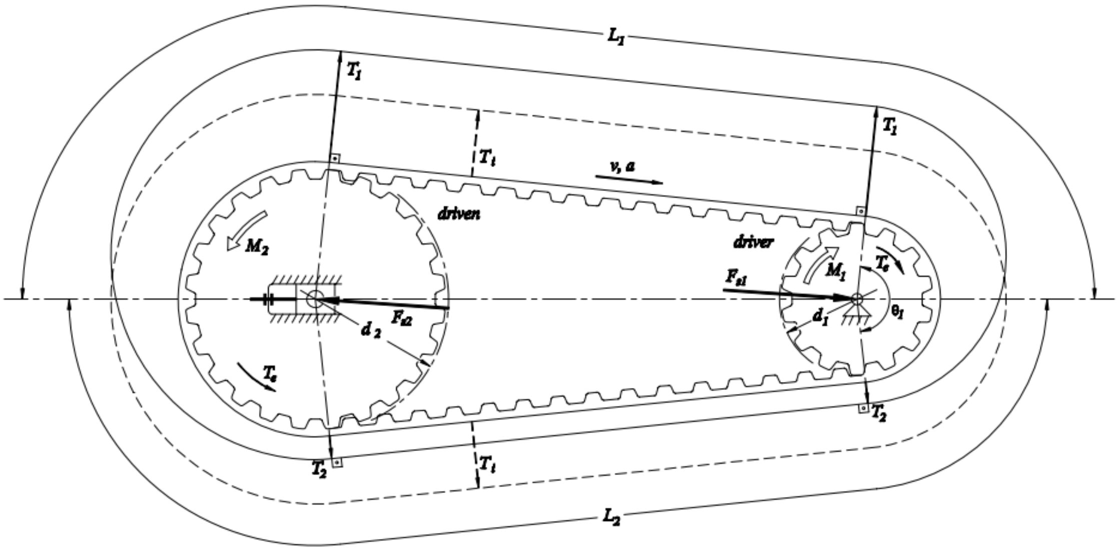

Figure 1.5.1. Forces in timing belt system [1]

$$T_e = T_1 - T_2 \tag{1.5.1}$$

Here T_1 – tight side tension and T_2- slack side tension.[1]

The driving torque is marked as M in the Figure 5. The pitch diameter of the driving pulley.

$$M = T_e \frac{d}{2} \tag{1.5.2}$$

The effective tension generated at the driver pulley is the actual working force that beats the over-all resistance of the belt movement. Resistance to movement comes from the driven pulley. The force transferred from belt to the driven pulley is the same effective tension force T_e. The torque needed for driver pulley can be expressed as:

$$M_1 = T_e \frac{d_1}{2} = \frac{M_2}{\eta} \cdot \frac{d_1}{d_2} = \frac{P_2 d_1}{\omega_2 \eta d_2} = \frac{P_2}{\omega_1 \eta} \tag{1.5.3}$$

M_1- driving torque; M_2 – torque needed for driven pulley; P_2 – power required at the driven pulley; ω_1, ω_2 – angular speed of the pulleys; d_1, d_2 – pitch diameters of the pulleys, η-efficiency of the belt drive (normally it is equal to 0.94-0.96).

The angular speed and rotational speed relationship:

$$\omega_{1,2} = \frac{\pi n_{1,2}}{30} \tag{1.5.4}$$

n_1, n_2 – rational speeds of the pulleys in rpm; ω_1, ω_2 – angular velocities of pulleys in rad. per second.

1.5.2 Shaft forces

A force balance at the driver or driven pulley relates tight and free side tensions and the shaft reaction forces F_{S1} or F_{S2}. In synchronous drive systems the forces on both shafts are equal in magnitude:

$$F_{S1,2} = \sqrt{T_1^2 + T_2^2 - 2 \cdot T_1 \cdot T_2 \cdot \cos\theta_1} \quad (1.5.5)$$

θ – belt wrap angle around the main pulley.

1.5.3 Timing belt pretension

The timing belt pretension or so called initial tension (T_i) is the tension force set by idler pulley. The idler pulley can be regulated. The correct pretension helps to prevent belt free side sagging and provides proper tooth meshing and whole system operation. In major situations the best performance of timing belt is when the magnitude of slack side is from 10 to 30 percent of the effective tension.

It is not recommended but belt drive system can proceed without belt tension part. It becomes possible cause after initial tension belt straights. Since belts have ability not to extend or creep it can be done but not recommended. The belt length stays the same during the process despite the load putted (at least theoretically). It is not good to forget that reaction forces can get very different under load. A slack with tight side tensions is the result not only of belt pretension or/and load, but on belt itself characteristics.

The adjustable tensioner idler is used in outgoing belt part cause it is better for belt tension control. Regulated idler tuning on the smooth side of the timing belt compensates for lengthening tight side. Smooth side tension is made by extra tension force F_e :

$$T_1 = T_2 = \frac{F_e}{2\sin\frac{\theta_e}{2}} \quad (1.5.6)$$

Where θ - belt wrap angle about the idler pulley [1]. This equation for effective tension combine to provide of the outgoing part from driver pulley to driven pulley belt tension T_1 and shaft reaction F_{S1} and F_{S2}.

Synchronous drive system with tension idler adds an extra load to the system and it is unable to be characterized by force alone. Counting tight and slack side tensions including shaft forces for a given torque or effective tension requires belt elongation to be puttes to the count.

Timing belt elongation becomes from pretension, belt sag and more factors that involves to a small elongation. Pulleys shafts and mountings is considered as a constant for analysis purpose.

$$\Delta L_{11} + \Delta L_{22} + \Delta L_{me} = \Delta L_{2i} + \Delta L_{1i} + \Delta L_{mi} \tag{1.5.7}$$

Where ΔL_{11}, ΔL_{22} is the tight and slack sides elongation caused by T_1 and T_2; ΔL_{me} is the whole elongation of belt when meshing with pulleys. $\Delta L_{2i}, \Delta L_{1i}, \Delta L_{mi}$ is deformation caused by the timing belt pretension T_i.

The majority cases has shown that belt elongation at the pulleys during pretension and in the process are basically the same:

$$\Delta L_{11} + \Delta L_{22} = \Delta L_{1i} + \Delta L_{2i} \tag{1.5.8}$$

The timing belt which is properly loaded the strain of the belt is proportional to the stress made to belt. The belt stiffness coefficient on tight (k_1) and slack (k_2) side equations are:

$$k_1 = c_{sp} \cdot \frac{b}{L_1} \tag{1.5.9}$$

$$k_2 = c_{sp} \cdot \frac{b}{L_2} \tag{1.5.10}$$

L_1, L_2 – Normal lengths of the slack and tight side. b is the width of the timing belt.

According to Hooke's Law that force needed to extend or compress a spring (in this case timing belt) by some distance is proportional to that distance.

$$\Delta L = \frac{T}{k} \tag{1.5.11}$$

$$\frac{T_1}{k_1} + \frac{T_2}{k_2} = \frac{T_1}{k_1} + \frac{T_1}{k_2} \tag{1.5.12}$$

$$T_1 = T_i + T_e \frac{L_2}{L_1 + L_2} = T_i + T_e \frac{L_2}{L} \tag{1.5.13}$$

$$T_2 = T_i - T_e \frac{L_1}{L_1 + L_2} = T_i - T_e \frac{L_1}{L} \tag{1.5.14}$$

Where L – the total length of the timing belt. In real life the timing belt can be created in the way that tension idler tensile the timing belts slack side from 10 to 30 percent of the effective tension.

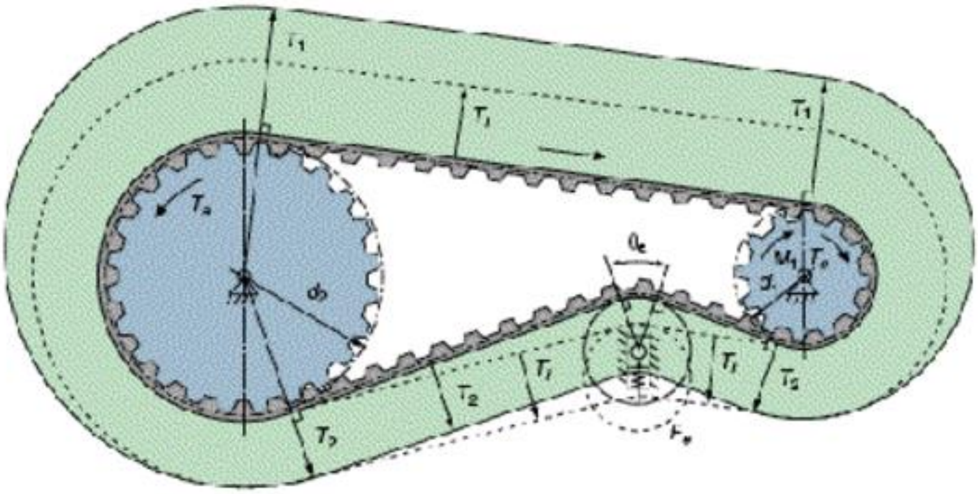

Figure 1.5.2 Tension forces in the timing belt system with tension roller [11]

1.5.4 Kinematics and friction in timing belt drive systems

The power and movement transfer with a help of the timing belt is influenced by the shape and the friction. In the moment of power transfer, the belt tooth enters the pulley groove and here starts forces to play. (Figure 1.5.2). In the time of the timing belt and pulley touches the tangential, radial and axial appears.

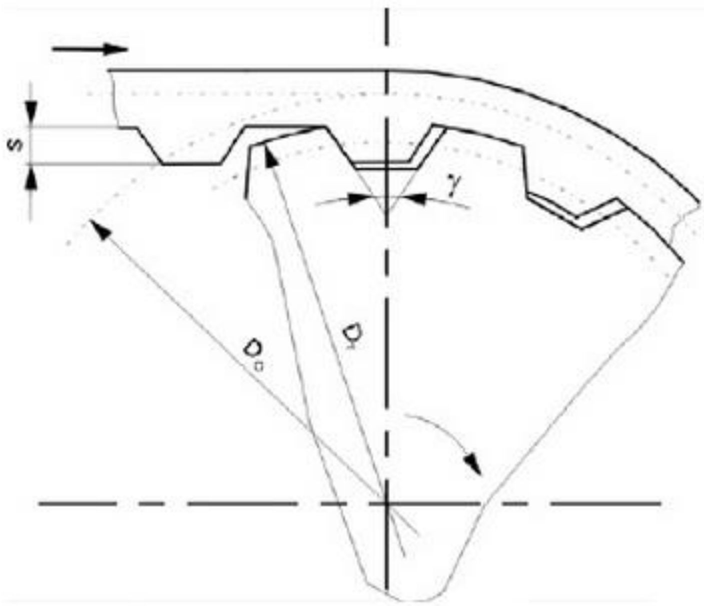

Figure 1.5.3 Belt and pulley layout

The side surface of the belt's teeth makes contact with the side surface of the belt pulley's teeth, after entering the coupling. Besides, the inner surface of the belt groove and the outer surface of the belt pulley and, from time to time, the front surface of the belt pulley with the flange ring, are in contact. The belt's tooth enters the coupling with the drive belt pulley, maximally strained due to previous tension. [15]

In the moment of belt entering the pulley, the belt tooth contacts the side of the pulleys tooth. During this, a line contact appears. In the case of interference the belt tooth pushes to the side surface of the pulley tooth. The deformation of the belts tooth appears , caused by the elastic characteristics of the timing belt. The deformation of the belt increases and at the same moment the contact area between the belt and pulley increases.

The main contact point moves from the pulley tooth to apex toward it root. The biggest tooth deformation occurs in second position showed ion the Figure 1.5.3. The value of normal force varies according to parabolic law, which leads to variation of the friction force. The greatest values of normal force and friction force are at the teeth's roots.

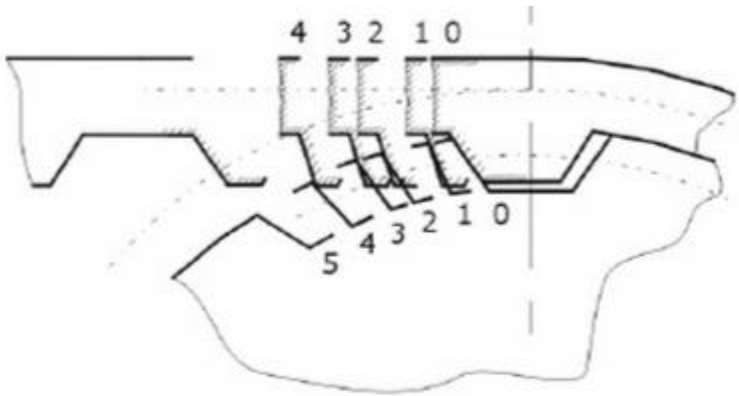

Figure 1.5.4 Belt entering the pulley layout [15]

The radial and centrifugal forces, the air addition, the extra radial movements of the belt appears. The sliding between pulley ant belt teeth appears in this motion. The friction force is larger than sliding friction force.

The bending and tension of the belt appears in this rotary movement. The belt bending can lead to total losses, as well as it leads to belt deformation. Also the force putted on the belts tooth decreases as it goes in the pulleys grove. The first timing belt teeth in the pulleys groove has the biggest load and it has the biggest deformation.

Pressuring the belt forward is caused by the influence of axial force. The timing belts practice showed that going to the sides of the pulley in its operation cycle if there is no control. In the situations where timing belt operates in high speeds or there exists quite long distance between the pulleys the belt going sides to sides is noticed the most. [15]

1.6 MULTIPLE LINEAR REGRESSION MODEL

Multiple linear regression statistical model was chosen for data processing. Multiple regression allows us to use mora than one criteria for the final prediction, normal (simple) linear regression allows to use just one factor. In short terms multiple linear regression allows us to separate casual factors and analyses the influences between them.

1.6.1 Multiple linear regression model theory

The Multiple linear regression model is:

$$y = X\beta + u \tag{1.6.1}$$

Here $y = (y_1, \dots, y_n)'$ is the data vector which consist of n observations on the response variable [13], X is a matrix $n \times (p+1)$ of explanatory variables, the first of which is a column ones, $\beta = (\beta_0, \dots, \beta_p)'$ is a $(p+1) \times 1$ vector of regression parameters is thought to be not random and $u = (u_1, \dots, u_n)'$ is an $n \times 1$ vector of random errors. If $\beta > 0$ this means that y is increasing, if $\beta < 0$ y meaning is decreasing. That increasing and decreasing meaning depends from our variables meaning sand coding. The coefficient β shows how much the meaning of the y is going to change by increase of X by one.

1.6.2 Requirements for data

The main requirements for data are:

- All data must be numeric (example: name of something must have a numeric symbol assigned),
- Depended variable must be normally distributed,
- The independent variable is measured without errors and they are not random. This requirement is not strict and can be interpreted, it depends from the situation and analysis points.
- The binominal variables are recommended to be coded to 0 and 1 (example: yes – 0, no – 1)
- Independent variables shouldn’t have strong correlation.

1.6.3 Model fit parameters

Regression model main fit parameters are:

- The determination coefficient (R^2). This is the main model fit characteristic which is mandatory for all the regression models. This coefficient checks the differences between Y meanings when the regression model is taken into account and Y meanings when it is not taken to account. The interpretation of the R^2 shows how many percent of Y reaction is explained by independent variables. It is bad when$R^2 < 0.25$. The closer R^2 meaning to 1, the better our model fits data.
- Adjusted R^2 is the alternative to R^2. It is used when in model exists many regressors and there are not so many observations.
- ANOVA p. This characteristic shows us if in model exists depend variables with regressors. If the p meaning is bigger than 0.05, this means that our model fit is very considerable. If it is opposite we got the confirmation that our model can fit data.
- DFB statistic. It measures of how much an observation has effected the estimate of a regression coefficient (there is one DFBETA for each regression coefficient, including the intercept).

1.7 STATISTICAL ANALYSIS SOFTWARE (SPSS)

Statistical analysis will be done by using SSPS statistical package.

SPSS – widely used program for statistical analysis in a lot of areas. SPSS Statistics is a software package used for statistical analysis. It was produced by SPSS Inc. In the year 2009 company IBM took over rights of SPSS. The newest version now is named IBM SPSS Statistics introduced in 2015.

Statistics included in the base software:

- Descriptive statistics: Cross tabulation, Frequencies, Descriptives, Explore, Descriptive Ratio Statistics;
- Bivariate statistics: Means, t-test, ANOVA, Correlation (bivariate, partial, distances), Nonparametric tests;
- Prediction for numerical outcomes: Linear regression;
- Prediction for identifying groups: Factor analysis, cluster analysis (two-step, K-means, hierarchical), Discriminant.

2. METHODOLOGICAL PART

2.1 TIMING BELT TESTING BENCH

For data gathering at first the testing bench is needed. The bench is considered to be an imitation of Ford’s 1.8 liter turbo diesel engine also well known in automotive world as Endura-D engine (engine code: C9DA or C9DB). It was chosen cause since it was released in the year 1998 it was the most popular car in the Europe for quite a long time of period.

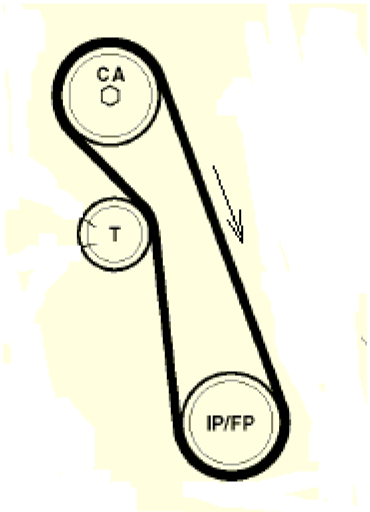

Figure 2.1.1 C9DA engine timing belt scheme [14]

CA is a camshaft pulley, IP/FP – injection pump/fuel pump, T – tension roller. The fuel pump itself is driven by the timing chain from the crankshaft.

In this synchronous drive system the FP pulley is the driver and the CA is the driven pulley. For test bench the fuel pump is replaced with electric engine with revs regulator. The electric motor is used from the polishing machine, because of the easy ability to regulate the revs and it has a reducer. The tension roller is regulated manually to get the wanted tension force. The deflection force will be checked with special tool for timing belt installation. It is shown in the Figure 2.1.2 below.

Figure 2.1.2 Belt tension meter by GATES company

The process of analysis will be in this order:

- Timing belt mounted on the bench with wanted tension application
- Bench powered up and the electric motor set to 350 revs per minute (injection pump rotation speed at engine idle) and let to spin for approx. 30 sec. when tension increased by 0.27 Nm (0.2 lbs.) and continued till the failure of the belt.
- Take the notice at what tension force the belt failed;
- Put another belt and repeat.

After all the information which needed is collected, the statistical operation will be done to find out timing belts endurance and their price association.

2.2 TIMING BELT SPECIFICATIONS

Timing belt is HTD style design belt. It has 91 tooth's and the length of the belt is 867 mm, the width 20 mm. The belt's tooth is 8 mm lenght, so this belt belongs to HTD8 timing belt group.

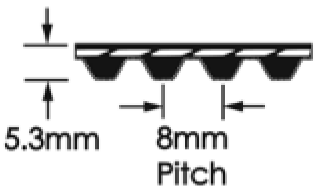

Figure 2.2.1 Timing belt pitch parameters

As shown in the figure below the standard timing belt upper part is made from polychloroprene, the main part is glass fiber cord in the middle, the teeth's are made from polychloroprene. The lower part of the belt is covered with polyamide. The timing belt structure materials can be different from the manufactures of the timing belt, some manufacturers can use carbon fiber, belt can be coated teflon for longer durability.

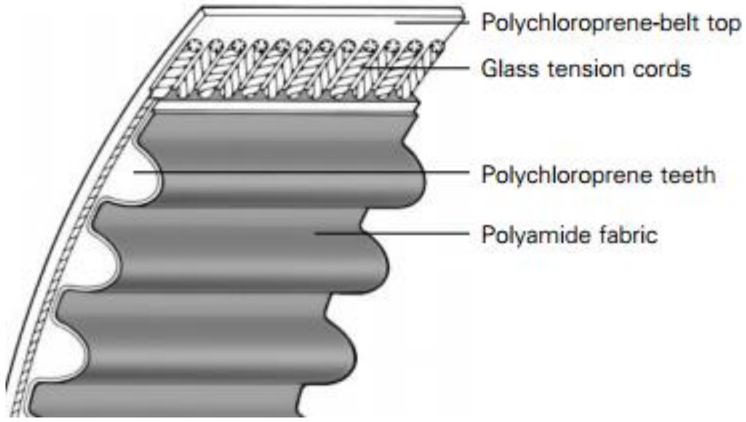

Figure 2.2.2 Standard structure of C9DA engine timing belt

The deflection force for this particular timing belt is from 2.7 to 5.4 Nm as shown in the table 2.2.1 below.

Table 2.2.1 Deflection force for timing belt

Belt Pitch	Belt Width, mm	Deflection force, Nm
HTD8 (8mm)	20	2.7 to 5.4
	30	4 to 8.13
	50	9.5 to 14.9
	85	14.9 to 25.7

3. RESEARCH PART

3.1 TIMING BELTS MANUFACTURERS

The main manufacturers of timing belts for cars are Continental, GATES, SKF, BOSCH, DAYCO. They are well known as the quality brands. Other companies as FEBI, Roulunds, Topran, AE, BGA, Flennor are not so well known. Of course these companies production is a little bit cheaper than the brand names creations.

Table 3.1.1 Average prices of timing belts my manufacturers and origin country

#	Parts code	Manufacturer	Avg. price in €	Made in
1	CT983	Continental	16	Germany
2	1 987 949 424	BOSCH	22	Germany
3	941009	Dayco	18	Italy
4	VKMT 04108	SKF	24	Italy
5	5541XS	GATES	14	Belgium
6	18976	FEBI	11	UK
7	302098	Topran	7.5	China
8	TB681	AE	7.2	USA
9	RR1142	Roulunds	11.8	Denmark

Average price is considered according to www.iauto.lt store website, collected on 2016-01-11. As we can see the price difference is up to 16.5 euros. Some of the companies is international and has the manufacturing facilities over the world, so other type of belt can be made in another country. The data of the manufacturing country is collected from this belt type backside. All timing belts has a date of the manufacturing printed on the belt or the package. All the subjects was made in 2015.

3.2 DATA RECODE FOR STATISTICAL ANALYSIS

We are going to use such data: manufacturer, deflection force applied, price and the country of manufacturer. Since for statistical software it is better to code some data groups into numeric scale. We are going to recode this data: manufacturer and the country of manufacturer.

Table 3.2.1 Manufacturer country recode table

Germany	1
Italy	2
Belgium	3
UK	4
China	5
USA	6
Denmark	7

Table 3.3.2 Manufacturer recode table

Continental	1
Bosch	2
Dayco	3
SKF	4
Gates	5
Febi	6
Topran	7
AE	8
Roulunds	9

The most important data is deflection force applied on the timing belt. All data gathered is shown in the Appendix table 1.1.

3.3 STATISTICAL ANALYSIS

3.3.1 Data review

The multinomial linear regression method is chosen for the statistical analysis. The depended variable is price in this model. The data frequency tables are shown below in tables 3.3.1-4

Table 3.3.1 Frequency table for manufacturing country

Country code		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1.00	20	22.2	22.2	22.2
	2.00	20	22.2	22.2	44.4
	3.00	10	11.1	11.1	55.6
	4.00	10	11.1	11.1	66.7
	5.00	10	11.1	11.1	77.8
	6.00	10	11.1	11.1	88.9
	7.00	10	11.1	11.1	100.0
	Total	90	100.0	100.0	

As we can see the countries with code 1 and 2 has 20 timing belts tested each, all others has 10 timing belts for research.

Table 3.3.2 The Price frequency table

Price		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	7.20	10	11.1	11.1	11.1
	7.50	10	11.1	11.1	22.2
	11.00	10	11.1	11.1	33.3
	11.80	10	11.1	11.1	44.4

14.00	10	11.1	11.1	55.6
16.00	10	11.1	11.1	66.7
18.00	10	11.1	11.1	77.8
22.00	10	11.1	11.1	88.9
24.00	10	11.1	11.1	100.0
Total	90	100.0	100.0	

The table 3.3.2 above shows the prices of the timing belts. As we can see the range of the price is from 7.2 to 24 euros. There are 10 variables and this means that the price was different for every one of ten manufacturers.

Table 3.3.3 The manufacturer (brand) frequency table

Brand code		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1.00	10	11.1	11.1	11.1
	2.00	10	11.1	11.1	22.2
	3.00	10	11.1	11.1	33.3
	4.00	10	11.1	11.1	44.4
	5.00	10	11.1	11.1	55.6
	6.00	10	11.1	11.1	66.7
	7.00	10	11.1	11.1	77.8
	8.00	10	11.1	11.1	88.9
	9.00	10	11.1	11.1	100.0
	Total	90	100.0	100.0	

The table 3.3.3 shows that here were nine manufacturers and 10 timing belts of each was tested.

Table 3.3.4 Deflection force applied when failure occurs

Def. force		Repeat times	Frequency	Percent	Valid Percent
Valid	9.18	1	1.1	1.1	1.1
	9.72	1	1.1	1.1	2.2
	9.99	2	2.2	2.2	4.4
	10.26	2	2.2	2.2	6.7
	10.53	3	3.3	3.3	10.0
	10.8	4	4.4	4.4	14.4
	11.07	3	3.3	3.3	17.8
	11.34	2	2.2	2.2	20.0
	11.61	2	2.2	2.2	22.2
	11.88	2	2.2	2.2	24.4
	12.15	5	5.6	5.6	30.0
	12.42	7	7.8	7.8	37.8
	12.69	2	2.2	2.2	40.0
	12.825	1	1.1	1.1	41.1
	12.96	9	10	10	51.1
	13.23	10	11.1	11.1	62.2
	13.5	3	3.3	3.3	65.6
	13.77	6	6.7	6.7	72.2
	14.04	2	2.2	2.2	74.4
	14.31	3	3.3	3.3	77.8
	14.58	4	4.4	4.4	82.2
	14.85	4	4.4	4.4	86.7
	15.12	5	5.6	5.6	92.2
	15.39	3	3.3	3.3	95.6
	15.93	3	3.3	3.3	98.9
	16.2	1	1.1	1.1	100.0
	Total	90	100	100	

From table 3.2.4 we can notice that at 12.96 and 13.23 Nm deflection force there was significant increase in failure.

3.3.2 Statistical model parameters

For statistical analysis some model fit parameters must be reached.

Table 3.3.5 Kolmogorov- Smirnov test

Parameters		manufacturer	Def_force	Price	Country
N		90	90	90	90
Normal Parameters[a,,b]	Mean	5.0000	9.6256	14.6078	3.4444
	Std. Deviation	2.59645	1.20836	5.64298	2.07235
Most Extreme Differences	Absolute	.113	.080	.135	.202
	Positive	.113	.065	.135	.202
	Negative	-.113	-.080	-.127	-.119
Kolmogorov-Smirnov Z		1.070	.763	1.281	1.912
Asymp. Sig. (2-tailed)		.203	.605	.075	.001

a. Test distribution is Normal.

b. Calculated from data.

The data distribution is normal, as we can conclude from the table 3.3.5. This is good for model fit characteristics.

Table 3.3.6 Variables selection for analysis summary

Model	Variables Entered	Variables Removed	Method
1	Country, Def_force, manufacturer[a]	.	Enter

a. All requested variables entered.

All variables were entered to the model, none of them were removed, and it is seen from table 3.3.6.

Table 3.3.7 Model summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.820[a]	.673	.661	3.28405

a. Predictors: (Constant), Country, Def_force, manufacturer

In the table 3.3.7, above the analysis model is summarized. From The R square statistical characteristic we can see that model fit for data is good. R^2 shows us how independent variable scatter around mean represents linear regression. Standard error of estimate shows 3.284. This characteristic is wanted to be as low as plausible.

Table 3.3.8 ANOVA parameter for model fit characteristic

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1906.534	3	635.511	58.925	.000[a]
	Residual	927.510	86	10.785		
	Total	2834.045	89			

Just to make sure that our statistical method is useful and meaningful we check ANOVA parameter. Our Sig. (significant coefficient) is 0, which is less than 0.05 and by this meaning we conclude that our statistical method is well chosen and its results can be taken to count.

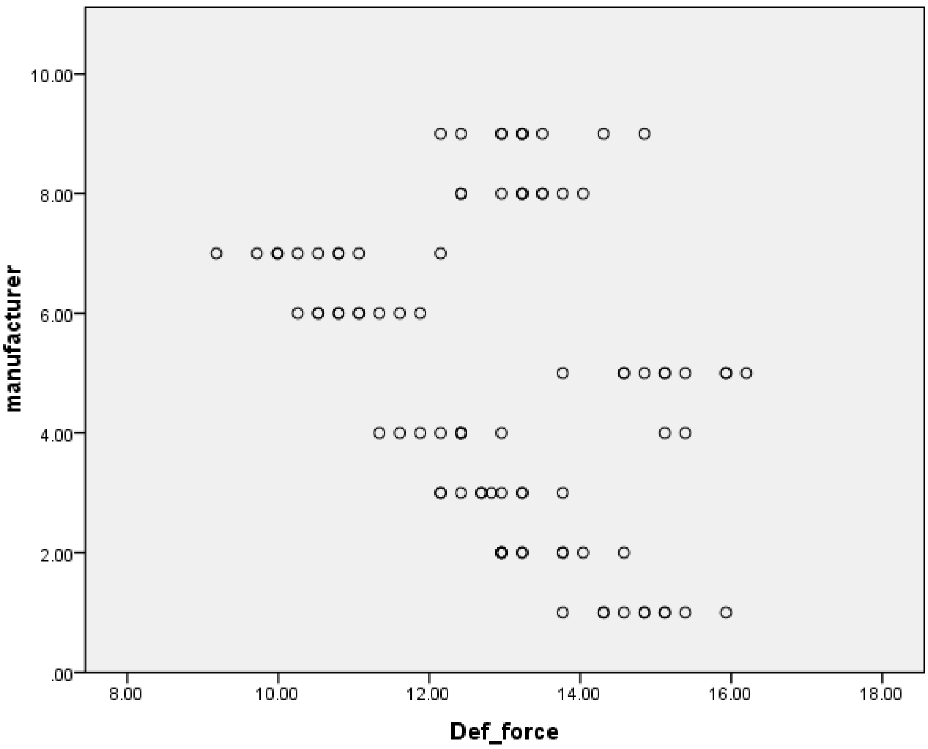

Figure 3.3.1 Manufacturer and resistance to deflection force illustration

In the illustration above the data interpretation between the deflection force and a timing belt manufacturer (brand). The manufacturers are coded to numeric standard, to recode you can view Table 8. This graph shows us that manufacturers with codes 1, 5 and 9 have better result than opponents. Those manufactures are Continental, Gates, Roulunds.

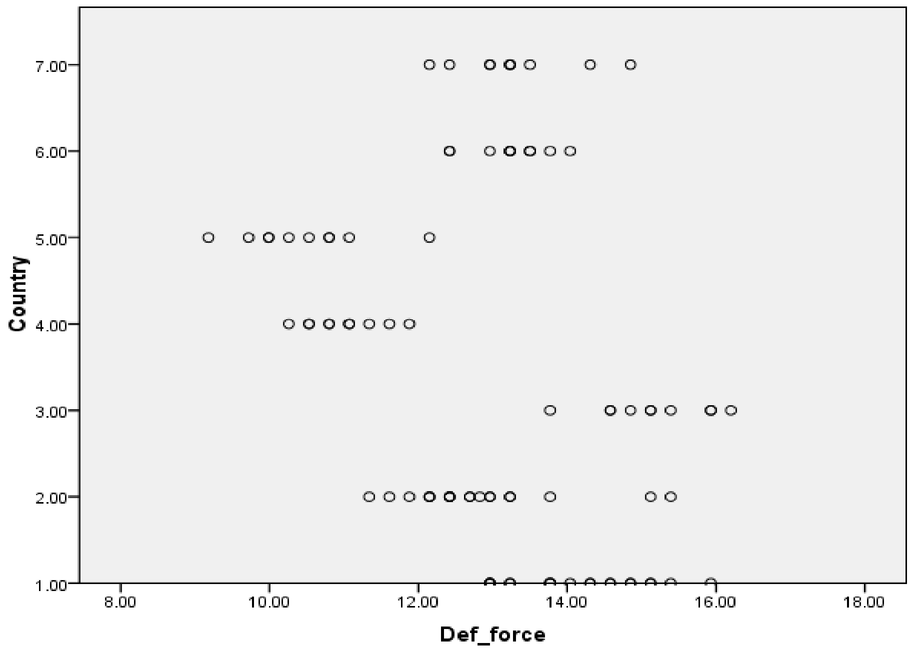

Figure 3.3.2 Origin country and resistance to deflection force illustration

Here in the figure 3.3.2 we can see that the best at the endurance test was the timing belts made in Germany and Belgium. The worst was the timing belt made in China and UK.

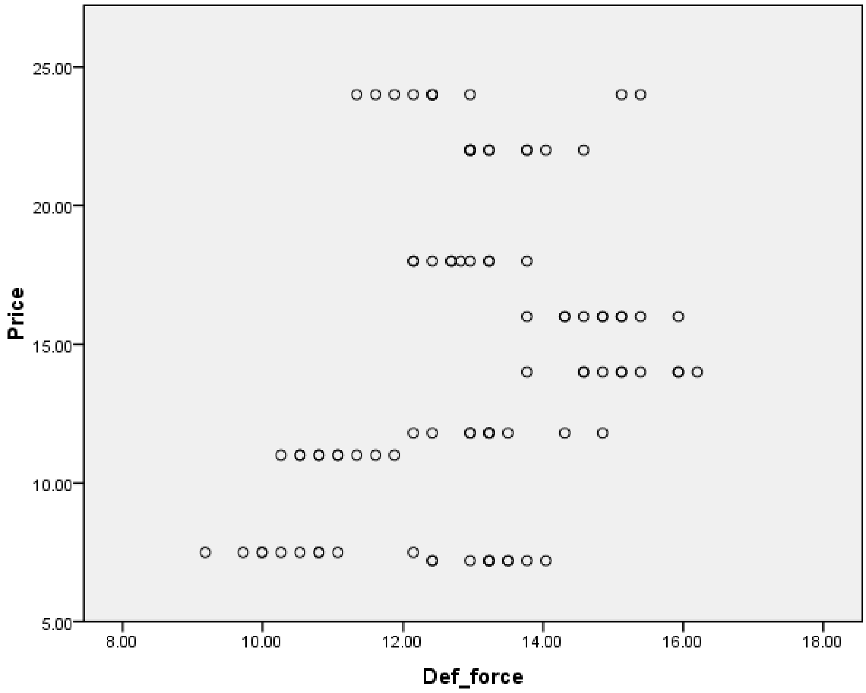

Figure 3.3.3 Price and resistance to deflection force illustration

In the figure 3.3.3 above we can see data relation visualization between the price and deflection force applied when belt failed. We can see that the best performance was from the average price timing belts (~14 EUR). It allows us to conclude from all the figures of relationship that it is more important to look at the price when selecting a timing belt than origin country and manufacturer.

Table 3.3.9 Linear regression coefficients

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	13.829	3.468		3.987	.000
	manufacturer	2.705	.724	1.245	3.738	.000
	Def_force	.592	.314	.127	1.887	.042
	Country	-5.356	.893	-1.967	-5.999	.000

This is the most important table (Table 3.3.9) from data analysis. It shows that all the variables are statistically significant, because every variable has his Sig. is less than 0.05 (confidence limit). Also we can see that the price is mostly influenced by origin country and a brand (manufacturer). The price of the timing belt is less influenced by endurance test result (the resistance to deflection force). The coefficient of deflection force is 0.592 this means that increasing in resistance to deflection force by 1.35 Nm (1 lbs.) increases the price by 0.592 euros.

Because there is linearity between the variables we can say that the more expensive belt gives us the better chance to get the timing belt with longer endurance, but not always the more expensive is better. The figure 24 has shown that the best at endurance test east the most expensive belt and few timing belts with the average price on the market. The cheaper product was not so good and the failure of the belt is more likely to occur.

4. SUMMARY AND CONCLUSIONS

- The literature review and information was collected and the testing bench was made to measure the endurance of the timing belt.
- The 9 manufacturer brands timing belts (10 of each) were purchased for the testing: Continental, Bosch, Dayco, SKF, Gates, Febi, Topran, AE, and Roulunds.
- The multiple linear regression statistical model was used to find the endurance, origin country and a brand name influence on price of the timing belt.
- The best in the endurance test was 4 manufacturers products: Continental (aver. 14.82 NM), Gates (aver. 15.14 NM) , Roulunds (aver. 13.28 NM) and SKF (aver. 12.77 NM).
- The best customer choice would be the timing belts with average price (~14 EUR). The Gates (14 EUR), Continental (16 EUR), SKF (24 EUR) and Roulunds (11.8 EUR) belts were the best at the endurance to tensile force test, but the price of the SKF belt is overrated because it was the weakest of this group of 4 and the most expensive of them all. The best choice would be Roulunds manufacturer timing belt, because it is the cheapest and equal in endurance.
- Statistical analysis showed that our deflection force when belt failed coefficient is 0.592 and this means that endurance in deflection force increase by 1.35 Nm (1 lbs.) timing belt price increases by 0.59 euro.
- For the more specific and deeper analysis the more data should be collected, but the analysis for that would be expensive and would took much more time so we can rely on this test during our decisions of choosing the timing belt.

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APENDIX 1

Table A-1.1. Data table

Manufacturer	Defl. force	Price	Country
1	11.2	16	1
1	10.6	16	1
1	11.4	16	1
1	11	16	1
1	10.2	16	1
1	10.6	16	1
1	10.8	16	1
1	11	16	1
1	11.8	16	1
1	11.2	16	1
2	10.2	22	1
2	9.8	22	1
2	9.6	22	1
2	9.6	22	1
2	9.8	22	1
2	10.8	22	1
2	9.6	22	1
2	10.4	22	1
2	10.2	22	1
2	9.6	22	1
3	9.8	18	2
3	9.6	18	2
3	9.8	18	2
3	9.4	18	2
3	9.5	18	2
3	10.2	18	2
3	9	18	2
3	9.2	18	2
3	9	18	2
3	9.4	18	2

4	8.6	24	2
4	9	24	2
4	9.2	24	2
4	8.8	24	2
4	8.4	24	2
4	9.6	24	2
4	11.4	24	2
4	9.2	24	2
4	11.2	24	2
4	9.2	24	2
5	11.2	14	3
5	11	14	3
5	10.8	14	3
5	12	14	3
5	11.8	14	3
5	11.4	14	3
5	10.8	14	3
5	10.2	14	3
5	11.8	14	3
5	11.2	14	3
6	8.2	11	4
6	7.8	11	4
6	8.4	11	4
6	7.6	11	4
6	8	11	4
6	8	11	4
6	7.8	11	4
6	8.6	11	4
6	8.2	11	4
6	8.8	11	4
7	6.8	7.5	5
7	8	7.5	5
7	7.6	7.5	5
7	7.4	7.5	5

7	7.2	7.5	5
7	7.4	7.5	5
7	7.8	7.5	5
7	8	7.5	5
7	8.2	7.5	5
7	9	7.2	5
8	9.6	7.2	6
8	9.2	7.2	6
8	9.8	7.2	6
8	10	7.2	6
8	10.4	7.2	6
8	9.2	7.2	6
8	9.8	7.2	6
8	10	7.2	6
8	10.2	7.2	6
8	9.8	7.2	6
9	9.6	11.8	7
9	9.8	11.8	7
9	9.2	11.8	7
9	9	11.8	7
9	9.8	11.8	7
9	9.6	11.8	7
9	10	11.8	7
9	10.6	11.8	7
9	9.8	11.8	7
9	11	11.8	7