UNIVERSITY OF PALERMO

FACULTY OF ENGINEERING

DOCTORAL PROGRAM IN ENGINEERING OF PRODUCTION

New frontiers of Robust Design with applications to motorcycles

GIOVANNI LO IACONO

XXII DOCTORAL CYCLE

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DOCTORAL PROGRAM IN ENGINEERING OF PRODUCTION

ING. IND. 16 – Industrial Engineering

New frontiers of Robust Design
with applications to motorcycles

GIOVANNI LO IACONO

Department of Industrial Engineering (DICGIM - UNIPA)
Statistics, Quality and Reliability Engineering group
University of Palermo
Viale delle scienze , edificio 8
90 128 Palermo - Italy
Tel +39 349 59 37 364
Email g.loiacono@dtpm.unipa.it

Tutor:	**Candidate:**
Ass. Prof. Stefano Barone	**Eng. Giovanni Lo Iacono**

Coordinator of Doctoral program

Prof. Livan Fratini

Abstract[1]

Most of the literature on Robust Design has so far focused on making technical performances of products and processes as much insensitive as possible to the action of noise factors, often representing physical variables. When studying the human-machine interaction, we can try to achieve system robustness to “human” noise factors in general, by considering variations in: psychological impact, body shapes and cognitive psychology in usage. These are new frontiers of Robust Design.

This work started from three research lines, namely Kansei Engineering, Robust Ergonomic Design, and Human Machine interface design, the former involving cognitive and psychological aspects within product placement, the second addressing human body variation, related to driving comfort and feeling, the latter focused on understanding a robust way to approach the Human Machine interaction in usage, tuning and optimizing physical, functional and dynamical characteristics of the motorcycle, also using the results of the first two research lines: machine features from the first and rider posture from the second.

A Six Sigma framework (Define, Measure, Analyse, Improve, Control - DMAIC) has been followed to better organize the flow of ideas for each field. The machine design is here figured as a process subjected to continuous improvement issue. DMAIC is just considered as a suitable framework showing how the different research purposes have been pursued during their development, as well as a research process can be approached like a production one: they both have input parameters, noise factors and final target.

The aim of this work is to show how to integrate three different fields in the early concept design phases of a new motorcycle model: the machine features/strengths (engine, brakes, power, shapes, preparation) defined under the customer perspective, the ergonomic interface, both static and dynamic, and finally the relation between machine geometric features and dynamic strengths, through the user style filter.

---

[1] Based on Chapter 2, “KAPPA: New frontiers of robust design to human variation”

Foreword

Within a never ending dichotomy between quantity and quality, their trade-off could be a goal for the modern engineering. Quantitative measurement of quality is today possible through sophisticated and reliable *frameworks* able to compare engineering solutions, for both products and processes, not only under a strictly technical perspective, but also through customer perceptions, as well as the final user of products and services.

How is it possible to predict in advance whether a solution is qualitatively sustainable, in order to avoid losses? It is widely known that a production process has to be preceded by a period of pre-industrialization, the technological transition, during which a technology, from a stage of embryonic research, must go through a time frame where the technological basis must change to let the value grow just in time for production start.

On the other hand, the production starts its "debugging process" only at the end of the technological transition, during which a good vision of all problems is strongly required, most of related to feasibility, especially under a scale economy perspective, and especially analyzing a wide scenario of product/process usage, and providing an umbrella sheltering from the inevitable changes affecting any real phenomenon.

The main goal of Robust Design is to find the best combination of design parameters for which the system response has the minimum dispersion around the nominal value, for any combination of noise factors values. This methodology needs to derive feedback from both experimental pre-industrial phases, and from the statistical quality control during the regular production. A product will be competitive only by observing the optimization process, from the opportunity window to the production start up.

The industrial sector we are going to focus on is the motorcycle one, where several experiences have been done by the author of this thesis during his professional life: in engines architecture at *Fiat Research Centre*, in motorcycles journals at *SuperWheels* and in motorcycle rental business at *Sicilymotorent* ®. Also one experience in aero engine sector is described: the six sigma project carried out with *Volvo Aero* during the period done abroad for doctoral program. The purpose of this thesis is to gather these different experiences and show the path followed to analyze them in the

Robust Design perspective, using also a framework borrowed from the managerial continuous improvement methodology “Six Sigma”.

The thesis consists of six Chapters and an Appendix: apart from the introductory Chapter 1, the Chapters 2-5 are related to five manuscripts either already published, or submitted for publication. Chapter 2 "KAPPA, New frontiers of Robust Design" takes the name from the KAPPA of PhD theses in the Swedish academic world, taken as a reference for its scientific production by the candidate starting from the period carried out at the "Chalmers University of Technology" in Gothenburg, during which also the work presented in Appendix 1 took place, "Low capability in the final machining for an aircraft engine component at Volvo Aero Corporation". This work is the result of a Six Sigma project, in collaboration with Volvo Aero, a well known Swedish company.

Chapter 2 is a chapeau for Chapters 3, 4, 5, regarding the response of the product "motorcycle" to the different noise factors, separately addressed. It is not meant to be exhaustive in terms of quantity. However, while offering a synoptic view of some of the topics covered in the thesis, it would be exhaustive in terms of quality. Its aim is to frame all the researches of this thesis within the Six Sigma methodologies. Chapter 3 deals with *Kansei* Engineering, or emotional engineering, a methodology created to direct the characteristics of the product in the market, and in this case to quantitatively correlate the variability of product properties with the variability of the emotions of potential buyers/users. Chapter 4 addresses the issue of anthropometric variation, and the effect it has on the perceived comfort, the latter treated in generalized dynamic conditions. Chapter 5 deals with man-machine interface, with interest in the variability of style and driving strategies. The methodology has been the basis for developing a software entirely dedicated to the simulation of rider-passenger-vehicle matching, from static to dynamic phases. Chapter 6 presents a structural application of the software, through which, in collaboration with structural engineers, an optimization of a motorcycle frame was made, starting from the simulation of human-machine interaction, rather than from fictitious load conditions. In this way HMI simulation begins to reveal its potential transversality in the design process, or Robust Design process.

Acknowledgements

This doctoral research, not supported by scholarships, was possible thanks to my strong will and passion for motorcycles, object of most of the related works, but also by the tenacity and generosity of Dr. Stefano Barone, who has allowed me to frame my passion in the subjects of an engineering of production PhD, giving me also the opportunity to spend a substantial and crucial period of study and synthesis at the "Chalmers University of Technology" in Gothenburg, Sweden.

List of abbreviations

DMAIC: Define Measure Analysis Improve Control
DOE: Design Of Experiments
KE: Kansei Engineering
KPC: Key Product Characteristic
HMI: Human Machine Interaction (Interface)
RD: Robust Design
RED: Robust Ergonomic Design
VMEA: Variation Mode Effect Analysis

To my wife

Table of contents

Chapter 1

Introduction to Robust Design

Introduction to Robust Design

1. Robust Design and product development process

According to the anthropologist J. G. Herder, the culture - determined by belonging to a particular historical and geographical context - is a "second genesis of man," whose way to satisfy needs is culturally determined. Industrial production is not exempt from this "cultural contagion": the way we work, and then industrialize, turns out to be the product of a culture that determines the competitiveness of an economic system in the world market place.

Product development processes, generally similar in different geographical areas, differ for effectiveness: the difference between Western and Eastern countries is evident, especially regarding the development time, where countries like e.g. Japan and Korea are very fast. Also the production capability level in time is different. For example in the Western world first serial products have always some problem, and a debugging phase is still required, when unexpected problems, often associated with equipment capability, are highlighted and eliminated. In the Eastern world first serial production is already debugged, and capability problems arise only at the end of the production cycle, when the equipment is close to replacement or dismiss.

Robust Design has been the success engine for the Japanese, quickly stepped up to excellent quality levels. Japanese have placed much more emphasis on quality design of products and production processes, compared to the western world. Both products and processes are designed so that external noise does not affect their performance. After the industrialization phase, it is crucial for companies developing the ability to reduce their product costs, nevertheless not affecting the quality levels required by the market: Quality Control and Quality Improvement are production techniques leading very high monitoring costs. During the setup phase, conceptual errors can be committed, and if severe, they can’t be recovered from the bravest marketing decisions. The need for expensive process controls could be reduced only by creating robust products and processes since their conception.

In particular, the methodology developed by Dr. Genichi Taguchi, widely known as *Robust Design* is characterized by the process parameters, as Quality Engineering: it leads to benefits such as increased productivity, improved quality, efficiency increase, increased reliability of processes and products.

Robust Design aims to eliminate the side effects without necessarily causes remove, being not oriented to validate a theoretical model describing a specific phenomenon, but only to find the best levels of the studied factors. This approach starts with the identification of control factors with a greater influence on the variance and then focuses on those affecting the mean response. It should be applied both to the product design phase, and to the production processes design. It is divided into:

- System Design: the aim of this phase is to design a system according to defined requirements. At this stage a choice of the most suitable technology (conceptual design) is required for the whole system, for subsystems, components and materials;
- Parameter Design: carried out the system design, it’s time to select the optimal values of design parameters. This phase is often skipped or done by trial and error, handmade managed with prototypes;
- Tolerance design: it is the next step leading to the variation reduction by setting and controlling the tolerances.

How does Robust Design fit into the value chain? Let us analyze a typical product development process. A first phase is followed by a subsequent development phase, until the definition of objectives, when it is possible to start talking about "process": in the early stages of setup and process-product development, the subsequent production phase has to be taken into account. Therefore everybody looks forward to the equipment definition, while the product-process system waits to be validated already. In the meanwhile the tooling phase must have been flown well, and, at the end of the product-process combination validation, production will start, closely followed by the commercial launch.

2. Robust Design to approach product/process development

In the value creation chain, once identified the product-process combination approaching stage as the most interesting one, let us contextualize the Robust Design role. Imagine a research center developing the binomial product-process for a client. While studying a new technology, having therefore already a significant distinguishing feature, and possibly covered by a patent, the task is to understand just in time irremediable defects of this technology, in which case the premature allocation will cause losses. The Robust Design will find a configuration of parameters eliminating these defects, regardless of any environmental change. If a new technology allows performing a task already performed by other technologies, with competitive but not significantly lower working time, then this technology can be sold to new competitors coming for the first time onto a market segment: they have no preference for a technology rather than another, at the same performance and costs level. In this case RD could help product-process development for customers, giving priority to equipment development. The research focus should be moved to process, because the technology itself doesn't make a new appeal for sales growth: it is necessary but not sufficient. Examples of such technologies are the rolling systems control valves for four stroke engines, far from the ideal expected electromagnetic controls, but more efficient than traditional tappet commands. A valve control robust design is expected to take into account in the design, the engine "timing" specifications, materials elasticity, cam profiles modelling tools radius, etc. ...

Some new technologies enable incremental contribution to competitiveness, by a step by step restyling, constantly improving the product appeal. An example may be the use of automotive hydraulic dampers or transmission couplings joint. These elements enhance some engine element noise, adjusting frequency by frequency, gradually improving comfort. Here the RD task, is to improve dampers technology, while allowing a wide range of materials to be manufactured with a perfect matching with the integrated system, in the most variable conditions. At the same time, however, the tight tolerances required by these elements production (especially the hydraulic dampers, such as hydraulic tappets), force the research team to closely monitor the quality. But if the test shows, with an experimental evidence, that the radial clearance does not affect the tappet performance, because oil meatus pressure allows wider tolerances, then a quite reprogramming of the machining tool will be opportune, or even a replacement with a less expensive alternative. At the same time a less rigorous sampling in the quality control will be acceptable. That's made thanks to RD.

If noise reduction is a "quality action" leading to incremental competitiveness, performances rather provide a competition gap jump, necessary and sufficient condition for sales. Let us now talk about the Common Rail © system, for example. The business drive concerning diesel high pressure injection technology, regulated by electronic control, was the turning point for diesel engines within

2000-2010 decade. While a technology is so required, know-how protection is fundamental: therefore the system is optimized at the source, being set and tuned by the first company developing the technology. Being the product a Black Box for customers, adaptable to all conditions, is a know-how protection guarantee, since the customer won't enter the component core. RD helps this adaptability and technology upgrades are ever entrusted to the patent owner for the next releases. In more complex technologies, several partners own the know-how, including details concerning construction and electronic controls, so optimizations in the advanced stage of industrialization, involve more subjects. Each actor applies its RD: research centers compensating usage conditions variation by using electronics, the injector manufacturer by calculating project tolerances in a robust way.

3. Robust Design on goal technology choice

Technologies and new products can be optimized in many ways. First, starting from the choice of the core technology. Let us take a view on the motorcycle market: Germans have always been supporters of cumbersome technical solutions, complicated and therefore expensive to develop, requiring a long time optimization (e.g. telelever front forks system on BMW or the rear drive shaft). For Italy, a brilliant choice of technologies is limited by the difficulty to optimize (for example the control system on Ducati desmodromic distribution). Japanese industry has always stood for rather simple solutions, but very well optimized, especially in the short term, resulting in sales and margins exponential growth: this has been possible mainly thanks to Robust Design, as a production less variable and more centred on the nominal values, allowed by the knowledge of the best parameter combinations (easier to discover in simple systems), typical of RD, provides much higher reliability compared to a distribution centred but more variable. As a result, out of one thousand Japanese motorcycles stock, there may be three evident defects and the parts will be replaced under warranty, while all the items are sold, while elsewhere in Italy or Germany, three motorcycles out of thousand do not exceed quality controls and won't be available for sales, while others 997 items behave quite differently item by item, with a significant number of unsatisfied customers.

Ultimately the idea of RD is to make a product insensitive to variation in the operating conditions, and the process insensitive to variability of materials, components, etc. before the start of a regular production phase. For this reason, a sensitivity analysis of all variables and parameters is necessary already in the process approach, starting with the low cost parameters. There is no need to check sources of the drawbacks: product design has to be immune to the variability of these sources. This rationale achieved for product features or typically measurable process (such as sizes, mechanical properties, specifications) can be extended also to the mere customer or worker perception. The purpose of this thesis, as will be explained in Chapter 2 is to perform - using the Six Sigma framework - measurable quality analysis and measurable quality perception analysis, under the perspective of non-experts, as well as the real final users of a product/process.

References

Andersson P. (1997). On Robust Design in the Conceptual Design Phase: A Qualitative Approach. Journal of Engineering Design, 8(1), 75–89.

Barone S., Lo Iacono G. and Pampinella S. (2010). Progettazione emozionale statistica: esempio di applicazione a moto di media cilindrata. ATA – Ingegneria dell’Autoveicolo, 63(7/8).

Barone, Lombardo and Tarantino (2007). A Weighted Logistic Regression for Conjoint Analysis and Kansei Engineering. Quality And Reliability Engineering International, 10.1002/qre.866.

Barone S., Lo Franco E. (2012), Statistical and Managerial Techniques for Six Sigma Methodology. Wiley.

Bergman, B., Klefsjo, B. (1994). Quality: from customer needs to customer satisfaction. Lund, Sweden: Studentlitteratur

Centro Ricerche Fiat (2003), Master of Managment:

- Albizzati, From the idea to market: business development and planning;
- Carrea, Scouting Technology: From Technologies to Market;
- Di Lucchio, Skills and innovation in product development;
- Morra, The curve of life and vitality of an enterprise;
- Scapaticci, Technology transfer;
- Volante, The risk management: product risk and initiative risk.

Hasenkamp T., Arvidsson M., Gremyr I. (2009). A review of practices for robust design methodology. Journal of Engineering Design, 20(6), 645–657.

Nagamachi, M. (1989). Kansei Engineering. Kaibundo, Tokyo.

Montgomery, D.C.(2005). Design of Experiments. 5th Edition. McGraw-Hill

Chapter 2

KAPPA

New frontiers of robust design to human variation

Application to motorcycle concept

A preliminary version of this work is included in Proceedings of the conference "11th Annual Conference of the European Network for Business and Industrial Statistics (ENBIS)", Coimbra-Portugal, 4-8 September 2011

KAPPA

New frontiers of robust design to human variation

Application to motorcycle concept

Giovanni Lo Iacono & Stefano Barone

Abstract

Most of the literature on Robust Design has so far focused on making technical performances of products and processes as much insensitive as possible to the action of noise factors, often representing physical variables. While studying the human-machine interaction, we can try to achieve system robustness to "human" noise factors, by considering variations in: psychological impact, body shapes and cognitive psychology within the usage. These are new frontiers of Robust Design.

This work started from three research lines, namely Kansei Engineering, Robust Ergonomic Design, and Human Machine interface, the former involving cognitive and psychological aspects within product placement, the second addressing human body variation, related to driving comfort and feeling, the latter focused on understanding a robust way to approach the Human Machine interaction in usage, tuning and optimizing physical, functional and dynamical characteristics of the motorcycle, also using the results of the first two research lines: machine features from the first and rider posture from the second.

The aim of this work is to show how to integrate three different fields in the early concept design phases of a new motorcycle model: the machine strengths (engine, brakes, power, shapes, preparation) defined under the customer perspective, the ergonomic interface, both static and dynamic, and finally the relation between machine geometric features and dynamic strengths, through the user style filter.

Keywords: Robust Design; Kansei engineering; Ergonomics; Comfort assessment; Motorcycle design; Man–machine interaction; Digital mock-up.

1. Introduction

The behaviour of the potential customer on the very first approach is more conditioned by what he thinks by looking at the machine, than from what he feels by seating on the motorcycle. The ranking of the most important characteristics of a motorcycle design (Barone, Lo Iacono, Pampinella 2010), shows that the most important element on the motorcycle evaluation is the engine power and performance, elements known by press releases rather than by experience. Then optional and overall aesthetic follow. The ergonomics is at the 4th place, so definitively the first idea is related to previous knowledge and aesthetic elements. On this basis we can assume that the handling of the motorcycle steps from the very first impact of the potential customer, or user, with the machine, although in general the effect of the external shape on the physical usage is underestimated.

Customer feeling is something that can be hardly measured: driving comfort feeling is a pre-requisite for safety, but its fine tuning can be done after product specifications are frozen, while psychological feeling assessment would assume a central role on very early phases of product development. The handling of the motorcycle is the output of several elements like the engine performances, being the torque more important than the power (although power is more important for communication and so from the psychological point of view), the weights distribution rather than the global weight, the brakes modulability rather then the braking power, the suspension harmony in the ride. However the subjective perspective comes from the skills and the strengths of the rider, who is also influenced by external elements like previous knowledge (from the press releases and communication in general) or the aesthetics, and lastly the ergonomic feeling.

$$\boxed{d = \int_{function}^{form} \left(\frac{T_{ech} E_{rg} S_{oc}}{t} \right)^{i} D}$$

Figure 1. Abstract design formulation (Biennale Milano, 2010)

By gathering all these elements, it is possible to highlight three areas: firstly the product placement specifications, as the segment, the engine power, the performance levels of brakes and tyres, are output of the target product, defined by cognitive and psychological aspects of potential customers; secondly, the geometrical dimensions of the human machine interfaces (handlebar, seat and footboard) are related to population anthropometrical data, determining the ergonomic feeling; third, the weight and the stiffness of the motorcycle depend on the frame design, whose stress levels are determined by the input forces generated by dimensions and weights, all these features addressing the handling feeling. So it is possible to that say all design process is feeling based, being these feelings respectively belonging to social, ergonomics and technology area. As a confirmation we found in modern art literature an abstract concept expressing design as a function of technology T, ergonomics E, and social factors S dependent on time t, raised to individuality i and then multiplied by personal input D, all this integrated from function to form (see Figure 1).

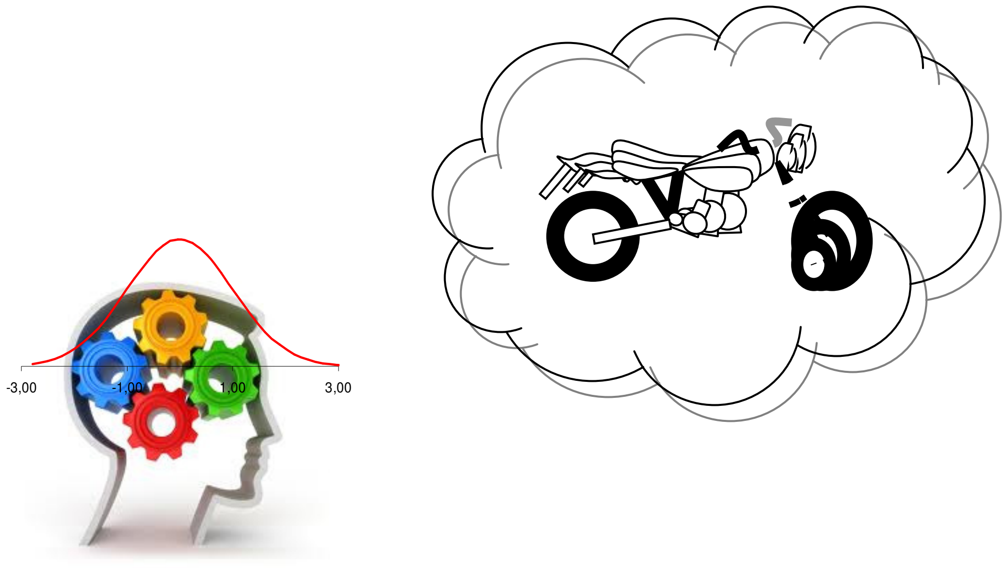


Figure 2. Design parameters variation and psychological noise factors

What our multicentric perspective wants to deal with, is the effect of the psychological, anthropometrical and cognitive noise factors in the general performance of the motorcycle. Our goal will be to achieve a general methodology to analyse and control these factors within the global performance, by defining and measuring specific indicators.

It is widely known how difficult is to detect the weights of motorcycle and subjective strengths inside the overall performance. What we did is to separately evaluate the merely psychological, anthropometrical and cognitive weights on the process, with:

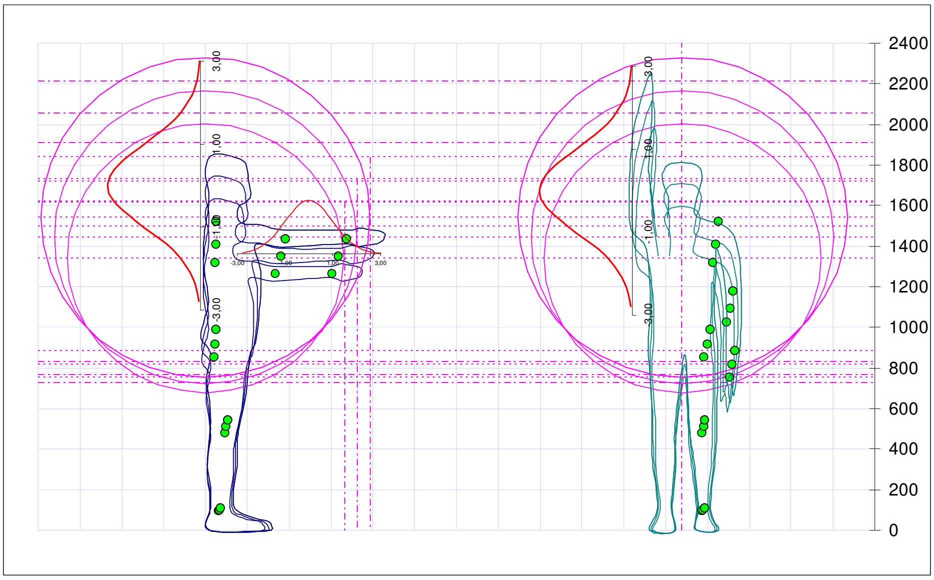


Figure 3. Human shapes variation related to anthropometrical noise factors

1) a kansei engineering analysis giving us a feedback on the design impact feeling of single motorcycle components, in order to understand the effect of psychological noise factors within product placement;
2) a static and dynamic matching of user and machine under a strictly ergonomic perspective, Robust Ergonomic Design, to comfort assessment and in order to understand the effect of anthropometrical noise factors within product development;
3) a dynamic simulation based on physical equilibrium to look at the general dynamic response of the motorcycle, searching for robustness to cognitive noise factors determining different driving styles, within the product refinement.

The Robust Ergonomic Design methodology allows designing products whose ergonomic performances are insensitive to the anthropometrical variation in product usage.

As main common purpose of each field, a certain stability to external and internal noise factors is required: accordingly the psychological-kansei aspects, being related to a real experiment phase, mostly rely on the adoption of DOE, while the ergonomic evaluations, done through computer experiments, turn around the central concept of LOSS FUNCTION. For the motorcycle dynamic response, the Robustness has been achieved simply by selecting and composing several user cognitive control logics, while simulating the ride: here six sigma techniques as VMEA and DOE. have been used.

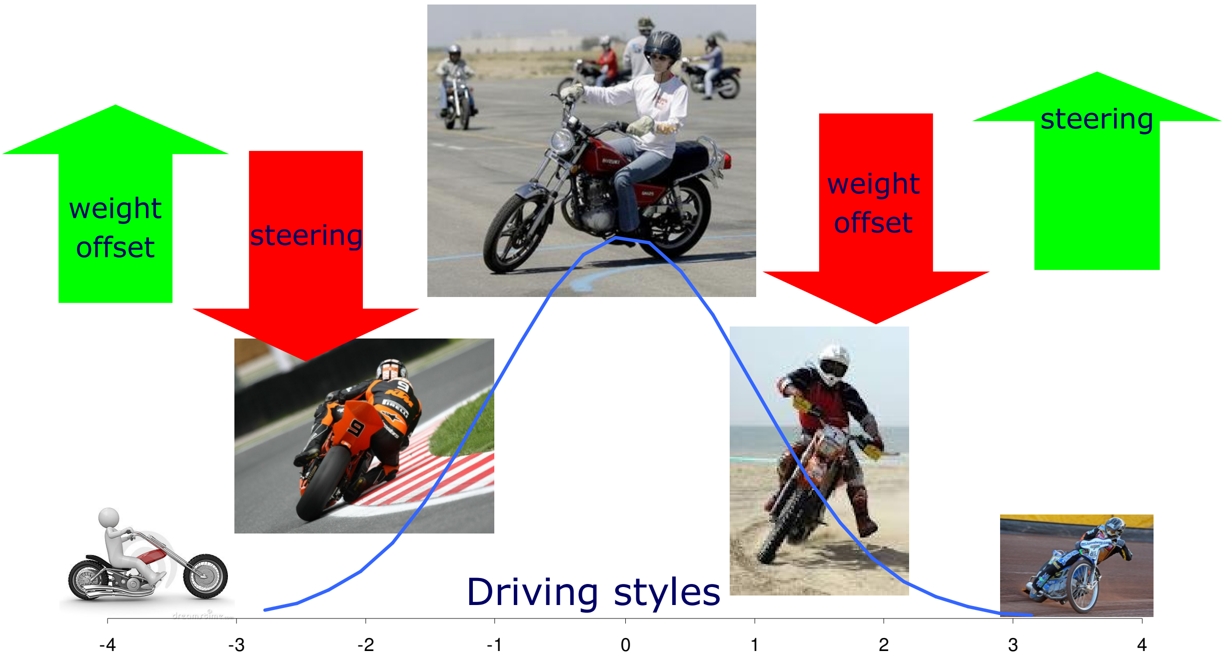


Figure 4. Driving style variation connected to cognitive noise factors

The first thing we needed to evaluate the performances of these three fields was to define a synthetic characteristic, its dimensions, and tolerances. A Six Sigma framework has been followed to better organize the flow of ideas for each field. Six Sigma is a mix of statistical and managerial methodologies, useful to bridge the gap between research language and real daily requirements of a modern company involved in production or services. A continuous improvement technique starts from an existing process and improves it by framing its analysis within a standard procedure involving a massive use of both statistic and managerial methodologies. The time schedule of this frame is described by DMAIC wheel, including five steps: Define, Measure, Analysis, Improve and Control phases. The machine design is here seen as process subjected to continuous improvement issue. The purpose of this chapter is to merge the different research lines of this thesis, and to show the path we followed to get the final shapes of them. Six Sigma is just considered as a suitable framework showing how the different research purposes have been pursued during their development, as well as a research process can be approached like a production one: they both have input parameters, noise factors and final target.

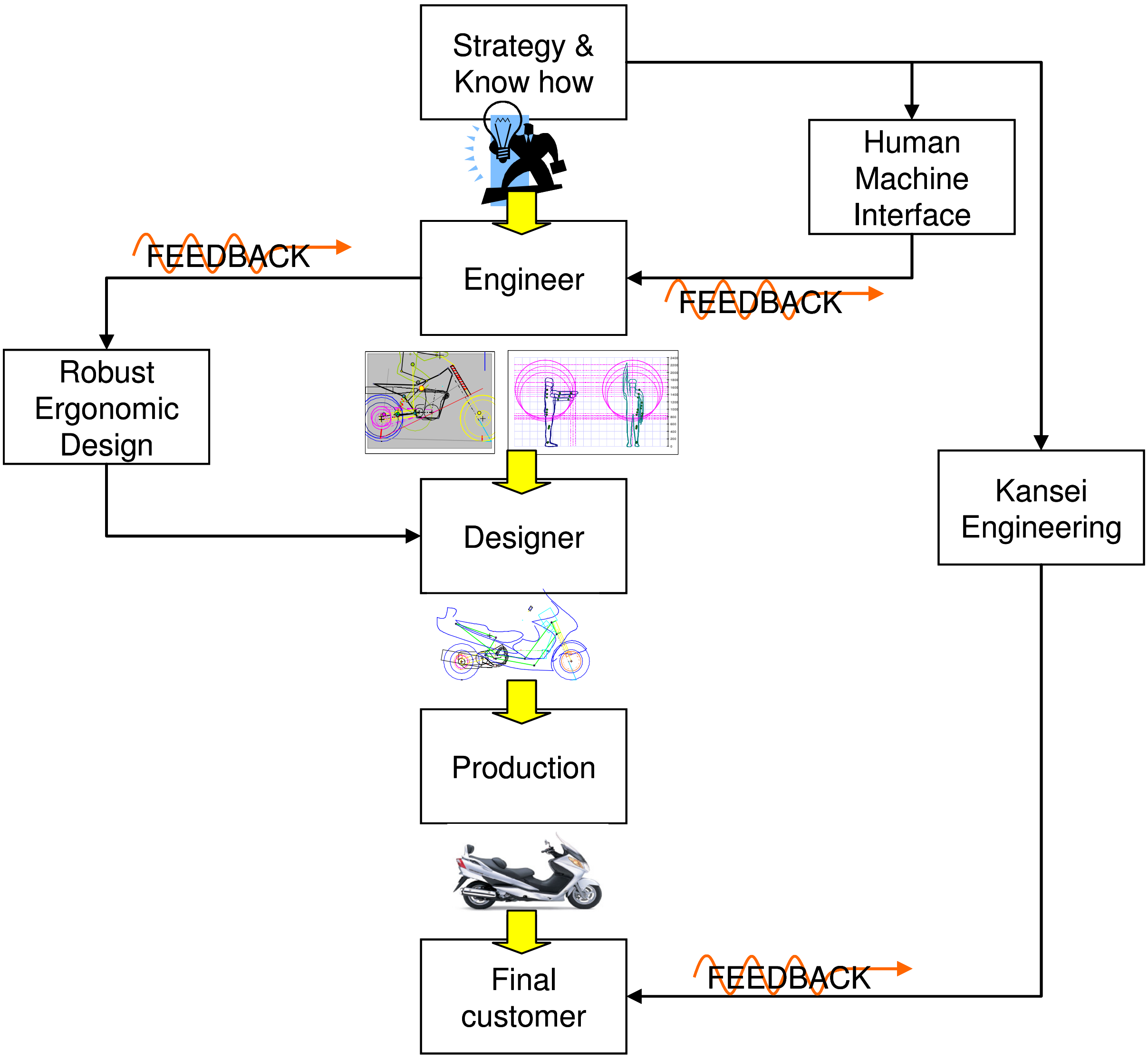


Figure 5. The research lines within the value creation chain

Figure 5 shows the research lines treated in this thesis within the value creation chain, starting from the head of the company, owner of the related knowhow. Here lies the knowledge of HMI. All the knowhow is entrusted to the engineer, whose role is to plan the product considering the company tradition, the human resources, the equipments. Dealing with the engineer about technical constraints, among whom is ergonomics and RED, the designer then gives a physical image to this mix, and production starts. Final product has to fit the customer requirements and needs. This is the first issue we are going to afford, using KE.

2. Robustness to psychological noise factors – Kansei Engineering (KE)

Getting started with Kansei Engineering for the evaluation of the psychological impact of the product, in order to build a model as much insensitive as possible to the action of the noise factors, we needed the subjective judgements, about single product attribute (or property), from a real sample of potential customers: it is still hard to make a psychological simulation (while it has been possible to make a physical one for Robust Ergonomic Design).

We want to translate feelings and impressions about product attributes into product parameters, measure feelings and elicit relationships between certain product properties. In other words we need to orient the technological research, but there are surrounding noise factors, the non-controllable parameters, as within any experimental test: a) the not-investigated objects (for example the colour or the brand of the motorcycle); b) the variability of respondent preferences. In order to overcome the former, some experimental shortcuts help reducing noise effects, while the understanding of the latter is simply the goal of this investigation: by definition Robust Design techniques are in general useful to avoid noise factor effects by weighting the results (in order to get synthetic indicators, as loss functions) or simply by knowing the effect of each noise factor, but never trying to remove it.

A Six Sigma approach has been employed to follow the working flow while understanding how to apply Kansei Engineering to this specific product (see figure 6). The *define phase* concerns the product target, so here we use a “machine-centric perspective”. More specifically we defined the domain, or the target (race bike, tourism, urban, etc.). The choice of our domain is always related to the possibility to have a real sample of designs to really evaluate the related properties. Also a “semantic space” is defined in order to get a clear view of all the concepts and the ideas which a customer may utilize, at an unconscious level, while approaching the product. A “property space” containing the attributes we want to investigate is the last task within the define phase, during which the aim is to answer to the question: what is important for customers?

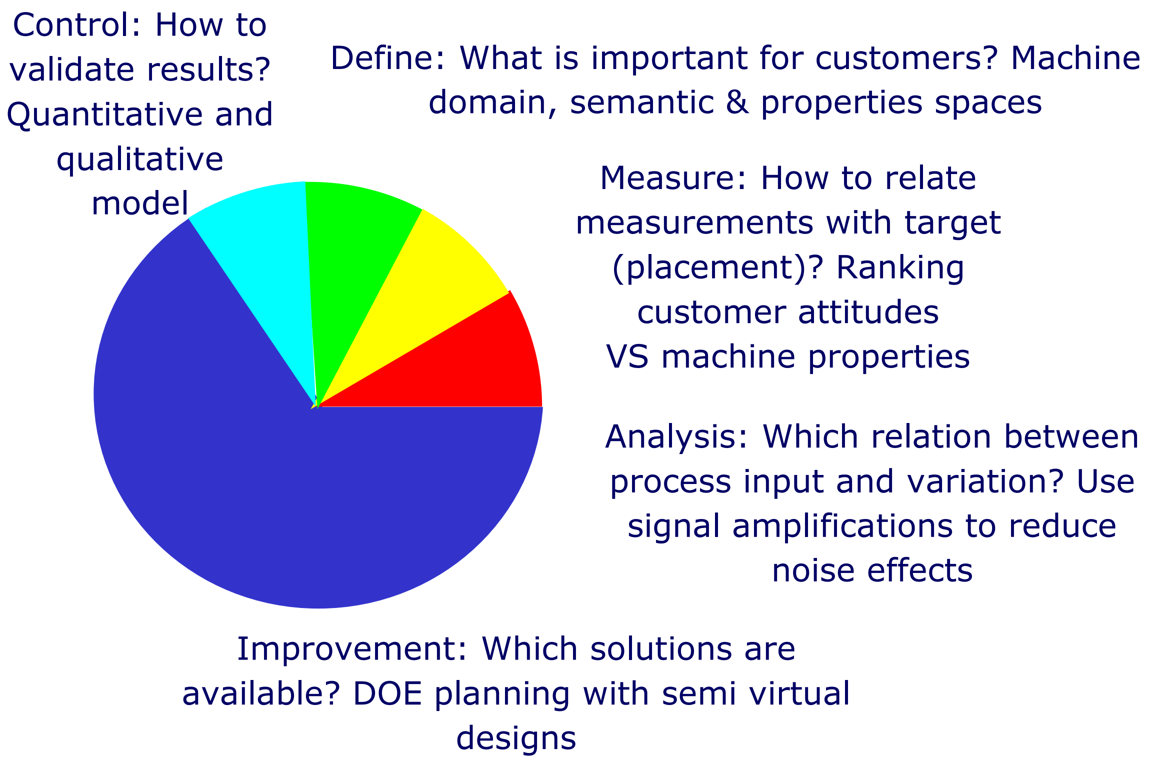


Figure 6. Six Sigma DMAIC wheel for customer ideas exploration - KE

In the *measure phase* the question is: How to relate the measures to the target? As well as the target is the knowledge of relationships between semantic and property spaces, the simplest measurement is the importance of the properties for the customer: then a customer sample is required to rank preferences among some properties of the specific product. Within the improve phase the ranking will be used to generate the Design of Experiments.

A qualitative model relating attribute levels to the semantic areas, is the final goal: in order to understand if chosen factors level changes are relevant or not, a selection of the significant output of the regression will be required within the control phase. Understanding how to help this selection is the purpose of the *analyse phase*, answering to the question: Which relation between process input and variation? Hidden into the variability of respondent preferences, there is an uneasy bug, which is the variability of the respondents ability to understand the impact of a single attribute merged within the entire product: a sort of second level noise factor, while the first level is the variability of preferences. A signal amplification is strongly required, and it is achieved by making a respondent calibration about single general issues before showing the dummy models, and then weighting each answer with the importance the single customer gives to each single factor.

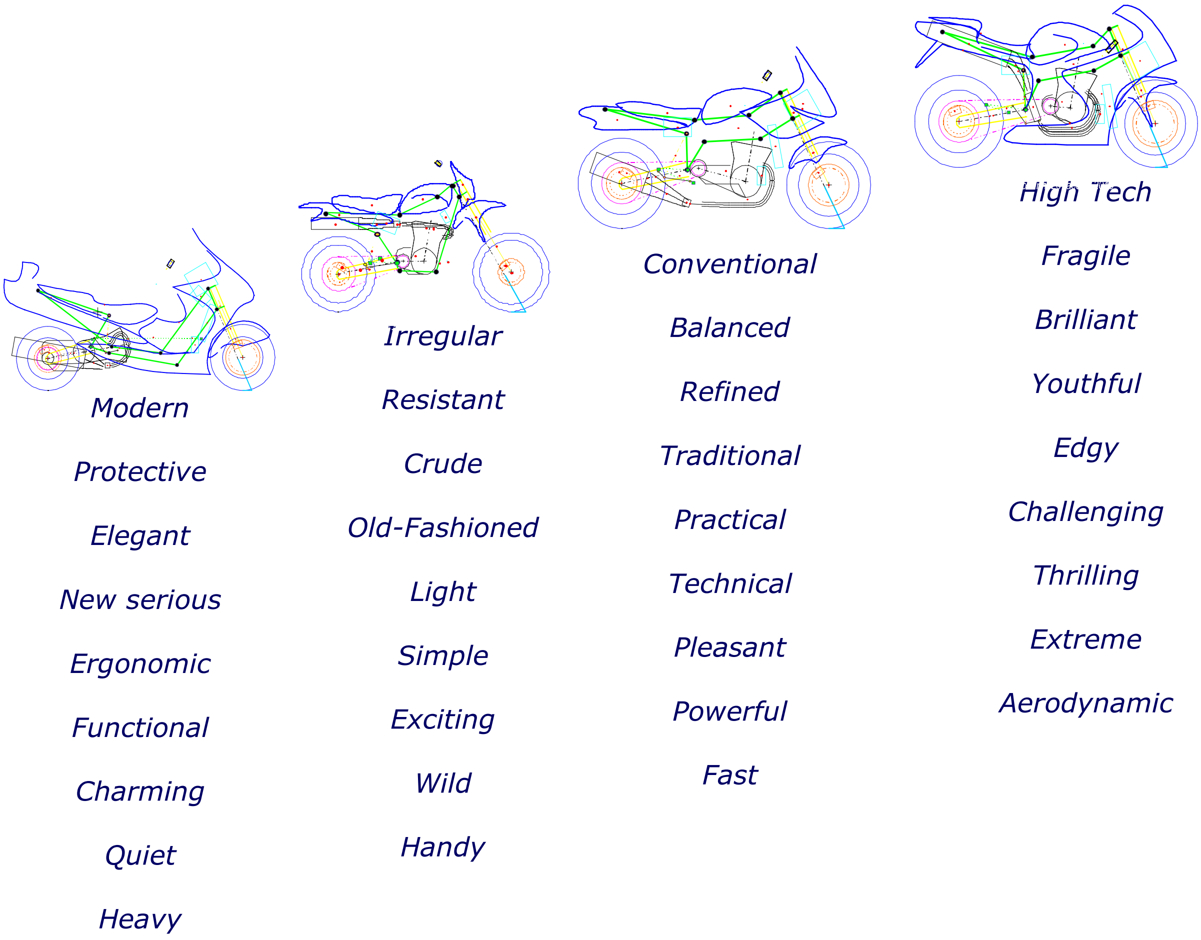


Figure 7. Design variations connected to market placement – Kansei words

The machine is the final target of all the process: within the *improvement phase* different real models or mock-ups, perceived as attributes assemblies, have to be tested with a significant sample of customers. This is represented as the larger step within the wheel because after the three steps theoretically approaching the issue, the research of the best mock up requires most of the time and money. By the way good define, measure and analyse phases help saving resources. The question here is: which solutions are available? The meaning concerns here the experimental solutions, as well as we need different designs to test the levels for the attributes highlighted by the customers as the most important ones. However only a trade-off between sorted-out factors and suitable ones allows preparing an experimental session. Several interviews, using prototypes, help measuring the semantic scale of the define phase. Obviously there is an exponential increase of noise factors.

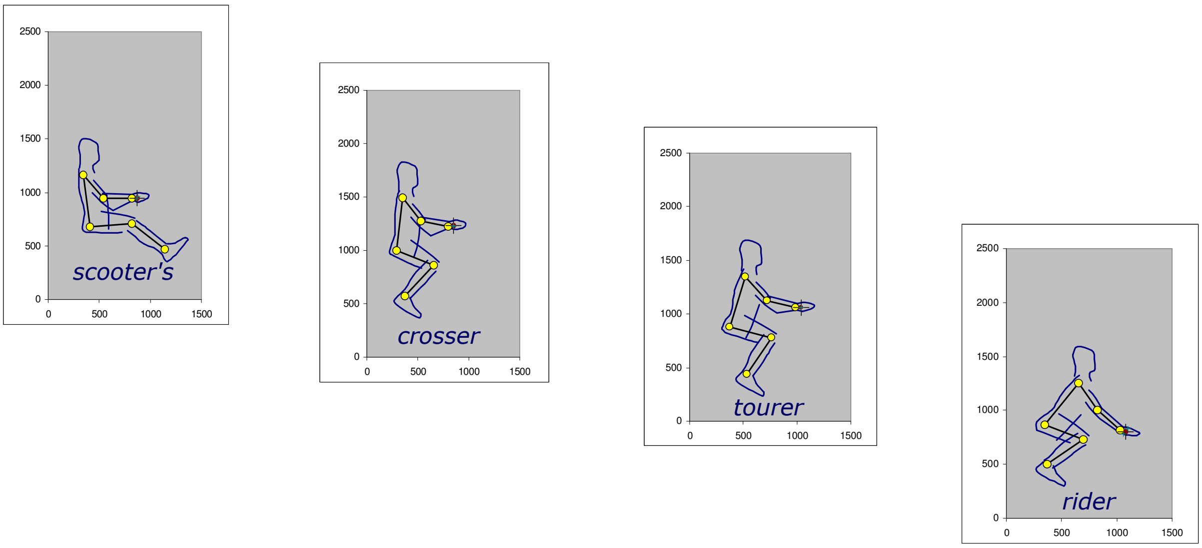


Figure 8. Human ideas variation (postures) property attributes

The related indicators on qualitative model, output of the investigation, can be analyzed thorough different designs within the final *control phase*, in order to better understand the impact of a wide choice of levels for a single attribute, while trying to answer the question: how to validate the results? Common sense helps understanding most of the sentences coming out from the picture, giving a feedback about methodology reliability also for more difficult issues.

Several attribute levels also generate different postures: comfort feeling starts from static trial (Barone, Lo Iacono, 2011), and a psychological attitude originated within the first approach affects also the following ones. Nevertheless the geometrical posture (see figure 8) is the most objective response of the customer to the attributes regarding it (seat, footboard, handle): there aren't noise factors related to psychological feelings, but only geometric interactions. In case of posture the KE model is almost ideal and then it can be suitable for the next issue, regarding only the ergonomic aspects related to posture and its noise factors.

3. Robustness to human shapes variation – Robust Ergonomic Design (RED)

We are interested in reducing the effect of body shape variation on riding comfort, so the simulation of the riding performance doesn't need a correlation with real judgements about the handling: we don't measure the handling but the physical fatigue of the rider within a perfect manoeuvre. That's probably an important part of the handling, but we are aware, as specified before, of how hard is to detect its objective measure from the subjective perception. So we limit our field to the physical fatigue.

Here the product which has to be insensitive to anthropometrical noise factors is still the motorcycle, but the real output of Robust Ergonomic Design is an early vehicle concept, made by specifications, and the customer is no longer the final user but the motorcycle designer, because our research is by now focused on a middle stage of product development process, where the output is the human model with its variability and the way to control it (see figure 5).

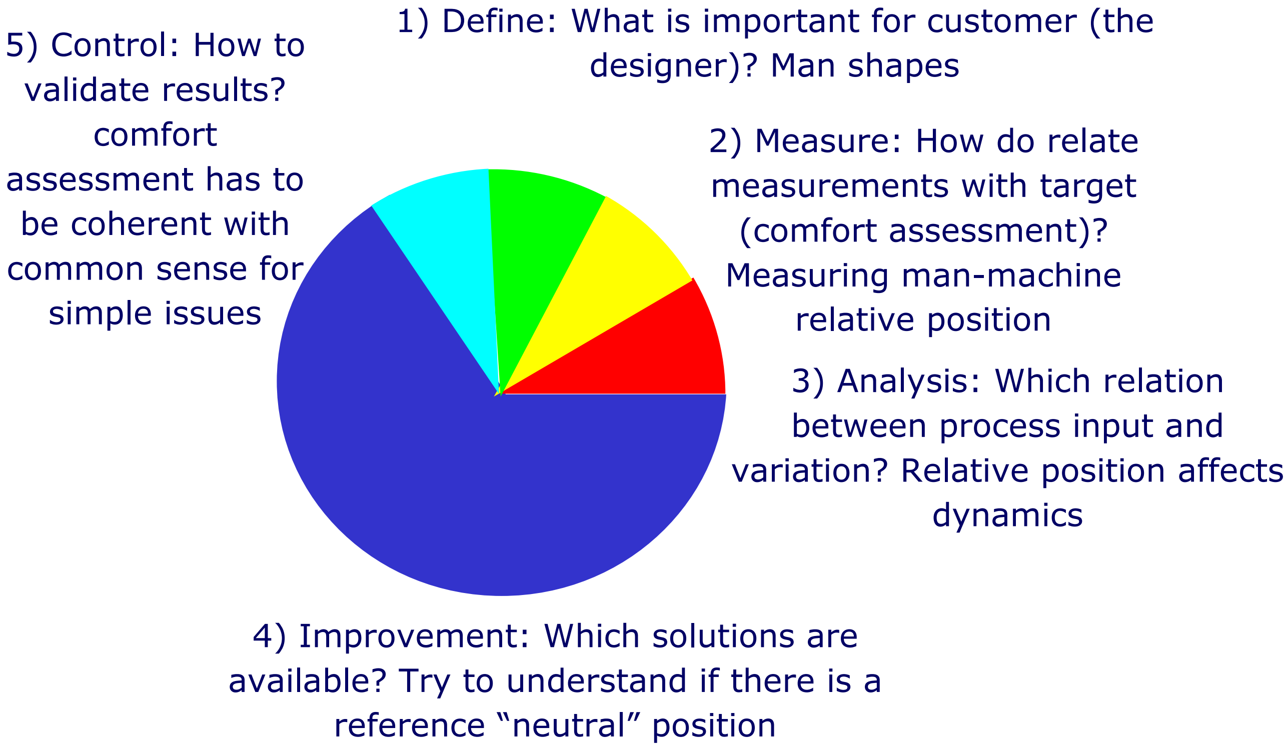


Figure 9. Six Sigma DMAIC wheel for comfort assessment procedure – RED

The DMAIC wheel of figure 9 shows the framework of the issue. Firstly, in *define phase,* we focused on defining the rider shapes and the concept of “Homocentric perspective”. Anthropometrical variation affects the joint angles, related to comfort feeling (Porter and Gyi, 1998). To model the anthropometric variability, the height of the human model is chosen as a synthetic variable. A parametric anthropometric model which could cope with variation among some percentiles has been computed, in order to get good results in the shortest possible time. A discrete approximation founded on some selected “percentiles” of the population is used.

The anthropometric model is useful to simulate the human machine integration, computing all the Joint angles for fixed ergonomic design. Posture can change when varying design parameters regarding the vehicle; this aspect was previously analyzed mostly by Barone & Lanzotti (2002-2008). The measurement of the effective posture is the second step in *measure phase*: it focuses on the geometrical relation between motorcycle and rider. In the *analysis phase* the comfort loss function is analyzed in a time-path simulation, in order to get an evaluation of the feedback from the user during the ride, understanding how noise factor affects the performance. Here motorcycle dynamics is heavily involved. In the following *improvement phase*, different comfort indicators are compared to understand their suitability for a synthetic statistical model, within the noise factor variation. The best one is a loss function where the preferred man posture is the starting point: the idea is to include the dynamic loads within the loss function, normalizing with the dynamic loads of a reference situation to get a dimensionless generalized loss function. As a final result, the evaluation of an optimal driving posture can be performed dynamically, involving forces on legs and arms. A generalized performance criterion, has been consequentially adopted: comfort feeling depends both on static position and on dynamic loads. In the *control phase* the best performance indicator is analyzed in order to be qualitatively validated.

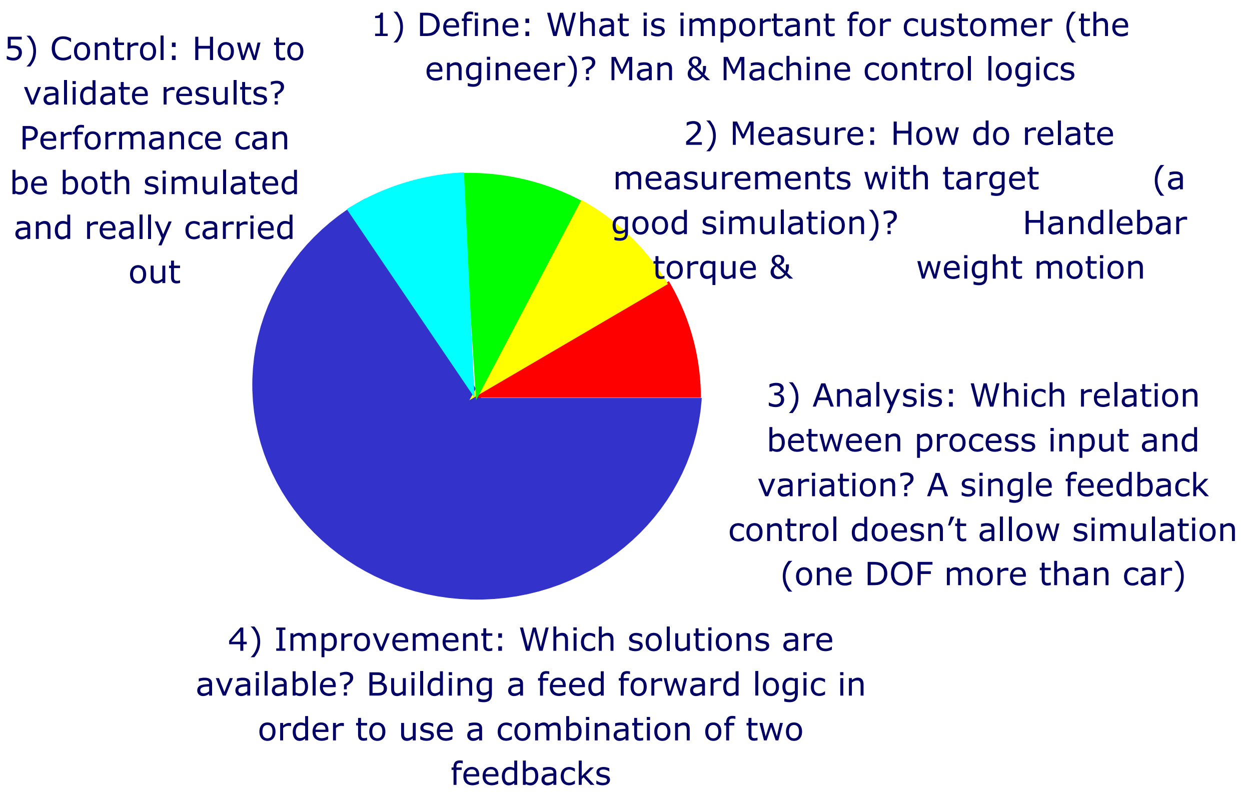
The aim of this RD application is to evaluate comfort over all, trying as much as possible to avoid subjective judgements while measuring stress on the rider or assessing a strength of the machine. Using a standard simulation to asses the comfort helps avoiding judgements: the human shapes are really just a Noise Factor. So it is compulsory providing a simulation which covers the entire path of the user/machine design, allowing to get a synoptic view of the product whose overall performance is the final objective. That’s the Human Machine Interface task.

4. Robustness to driving style variation – Human Machine Interface (HMI)

Speaking about Human Machine Interface, the human factor can heavily interfere with the real potentiality of the motorcycle: so a kind of “emotion filter” is required in order to obtain a feedback as much objective as possible. This result can be achieved by using a dedicated dynamical simulation software tool, including a driving logic as much insensitive as possible to the variation of driving styles. As a result, it is possible to make evaluations on dynamic and ergonomic performances of the vehicle under development.

The simulation is based on physical equilibrium laws application on an imposed trajectory, going on the “edge” of the grip field by tuning the lateral acceleration: so the riding time for a given path is an output of the simulation. In this simulation it is assumed that the response of the “motorcycle system” is optimal in terms of ideal steering joints, no friction bearings and constant grip coefficient for asphalt-tyres contact. Moreover the engine output is considered on a steady state torque, so neglecting the effect of the engine internal inertias but not the transmission and the wheels ones. The brakes are ideal, with an instantaneous response, but the input force at the lever is part of the riding strategy which is one of the rider’s control actions. The output is the result of the human-machine matching: it is not so easy to determine the borderline between rider’s control and machine intrinsic behaviour. The motorcycle dynamic strengths are determined by chassis dimensions matching tires and suspensions performances, whose outputs are the lateral acceleration and the yaw speed, the former being the higher the better, and latter to be kept under control in order to get a stable riding (Cossalter, 2002). The handling is generally an indicator of the easiness on the control actions, while the stability is the level of insensibility to the effect of external noise factors.

The path to describe this tool building takes place from the definition of the customer, in this case the engineer whom this tool, the product, is designed for (see figure 10). Within *define phase* the control logics have to be clearly specified: they are all the controls of the vehicle, regarding engine, steering, suspensions, all independent variables the whole system handles.


1) Define: What is important for customer (the engineer)? Man & Machine control logics

2) Measure: How do relate measurements with target (a good simulation)? Handlebar torque & weight motion

3) Analysis: Which relation between process input and variation? A single feedback control doesn't allow simulation (one DOF more than car)

4) Improvement: Which solutions are available? Building a feed forward logic in order to use a combination of two feedbacks

5) Control: How to validate results? Performance can be both simulated and really carried out

Figure 10. Six Sigma DMAIC wheel for driving strategy creation – HMI

Conversely in *measure phase* the focus is on the controls affecting variability in simulation, so only the ways the rider controls the vehicle stability, being the rider the only noise factor source, while making the conservative hypothesis considering power supply to be controlled by grip limit research, as it is in the worst case. Motorcycle has three degrees of freedom, one more than car, because there is the rolling angle. So more than steering action also the weight movement is required to control this additioned DOF: they both represent noise factors because their usage is unknown while depending on personal driving style. The driving strategy of the simulation has to be robust to this variation.

In the *analysis phase* the use of the single rider control logic leads to understand that a single feedback logic, as control trajectory with only the use of the steer, is not capable of controlling the simulation. The research of the optimal composition of control logics inside a feed forward strategy is the *improve phase* goal, while in the *control phase* the results of the best solution are compared with the ones coming from experimental tests done to validate the simulation.

Figure 11. Social scopes of human machine interface

5. Conclusions

The aim of this thesis is to get a picture of how the noise factors work, both in psychological feeling, ergonomics, and cognitive approach. In the three cases we had to deal with signals and noises: forces, product properties and man-machine binomial features as signals, while customer attributes perception, anthropometrical distributions and cognitive variations are the noise factors.

The aim of RD is not only make the product insensitive to the NF effects during the usage, but also to measure the effect of non controllable parameters. Therefore we provided a way to measure in an unbiased way the effects of details that seldom anybody considered measurable: a combination of three different DMAIC frameworks allowed to conclude a product design process, starting from product placement, then through a physical matching, and finally with a dynamic simulation of vehicle. Robust Ergonomic Design and Human Machine Interface support the “hardware”, as well as their outputs are designs or physical results, while Kansei engineering is the driving wheel of the investigation, as well as it gives a conceptual design, the fundamental guidance we need for the market we look forward to.

References

Barone S., Lo Franco E. (2012), Statistical and Managerial Techniques for Six Sigma Methodology. Wiley.

Barone S., Lo Iacono G. and Pampinella S. (2010). Progettazione emozionale statistica: esempio di applicazione a moto di media cilindrata, ATA – Ingegneria dell’Autoveicolo, 63(7/8).

Barone S., and Lanzotti A. (2009). Robust Ergonomic Virtual Design. In: Statistics for Innovation - Statistical Design of 'continuous' product innovation. Ed. P. Erto. Springer. ISBN: 978-88-470-0814-4.

Barone, Lombardo and Tarantino (2007). A Weighted Logistic Regression for Conjoint Analysis and Kansei Engineering. Quality And Reliability Engineering International, 10.1002/qre.866.

Bergman, B., Klefsjo, B. (1994). Quality: from customer needs to customer satisfaction. Lund, Sweden: Studentlitteratur

Chang, S., Wang M.J, (2007). Digital Human Modeling and Workplace Evaluation Using an Automobile Assembly Task as an Example. Human Factors and Ergonomics in Manufacturing, 17 (5), 445–455.

Chou, J.R., Hsiao, S.W. (2005). An anthropometric measurement for developing an electric scooter. International Journal of Industrial Ergonomics, 35, 1047–1063.

Chung, S.J, Park, M.Y. (2004). Three-Dimensional Analysis of a Driver-Passenger Vehicle Interface. Human Factors and Ergonomics in Manufacturing, 14 (3), 269–284.

Collins M., Brown B., Bowman K. and Carkeet A. (1990). Workstation variables and visual discomfort associated with VDTs. Applied Ergonomics, 21(2), 157–161.

Cossalter V. (2002). Motorcycle dynamics. Padova: Lulu.

Fritzsche L. (2010). Ergonomics Risk Assessment with Digital Human Models in Car Assembly: Simulation versus Real Life. Human Factors and Ergonomics in Manufacturing, 20 (4), 287–299.

Lance, C.E. and Woehr, D.J. (1986). Statistical Control of Halo: Clarification From two Cognitive Models of the Performance Appraisal Process. Journal of Applied Psychology 71(4), 679-685.

Murphy, K.R. et al. (1993). Nature and Consequence of Halo Error: A Critical Analysis. Journal of Applied Psychology 78(2), 218-225.

Nagamachi, M. (1989). Kansei Engineering. Tokyo: Kaibundo

Porter M. and Gyi D.E. (1998). Exploring the optimum posture for driver comfort. International Journal of Vehicle Design, 19(3), 255–266.

Wilson J.R. (2000). Fundamentals of ergonomics in theory and practice. Applied Ergonomics, 31, 557–567.

Chapter 3

Emotional Statistic Design:
middle size motorcycles application

Published on “ATA – Associazione tecnica dell’Automobile”, Vol. 63 - n. 7/8 July-August 2010

Ing. Produzione, DTPM Unipa, 15 Dicembre 2009

Emotional Statistic Design:

middle size motorcycles application

S. Barone*[1]*, G. Lo Iacono*[1]*, S. Pampinella

[1]*Department of Technology, Production and Managerial Engineering, University of Palermo, Viale delle Scienze,*
90128 Palermo, Italy

Abstract

In this paper the use of particular statistic techniques within Kansei Engineering will be shown, with an application to middle size motorcycles, belonging to medium range tourism vehicles. Following the purposed procedure, the "product motorcycle" has been analyzed from the perspective of the emotions arousing in potential customers, within the so-called *semantic space*.

At same time inside the *property space,* market specifications has been selected and gathered by using a software evaluating the importance of attributes or product characteristics. Then several interviews have been conducted in order to correlate the product characteristics, extracted from profiles selected within a balanced experimental plane, with the different semantic areas over mentioned

These interviews contemplate static trials of different product profiles, with an evaluation based on the respondents answers, measured over a semantic scale. Then, through an ordinal logistic regression, two models have been validated, describing relations between customers sensations and product characteristics.

Keywords: motorcycles, kansei Engineering, Anthropometry

Introduction

Kansei engineering can be defined one of the main product development methodology, since it translates impressions, feelings and customers requirements for existing products or concepts, in concrete project parameters (Nagamachi, 1989). Since 70's, when the methodology has been invented, several industries widely utilized it, spacing from automotive to fashion. The recent informatics evolution allowed its progress.

The present work objective is to further confirm, by experimental application, the importance of particular statistic methodologies within Kansei engineering. Also to show the potentiality of these techniques, by trying to identify the impact of the product object has on potential customers perceptions.

The motivation of this study is the increasing attention to the emotions weight on customers behaviour, and moreover the necessity of investigating the strategic implications, as well as operative, of the "emotional zone" on product sales, and on product development planning.

The paper is divided into three parts: in the first one the used methodology is explained, while the second part topic is the specific application to the case study. Finally on the third part, conclusions about the specific investigation object are deducted

1. Kansei Engineering: purposed methodology

The utilized methodology is shown on figure 1 (Schutte, 2002).

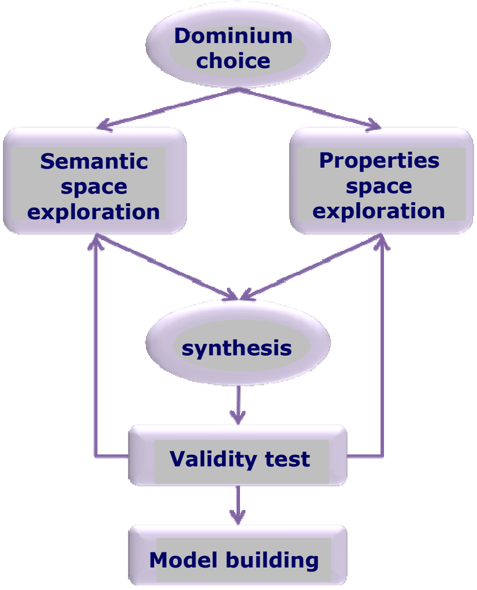


Figure 1. Purposed methodology

The dominium choice concerns the study boundaries definition, including the target group selection, the market segment, and the specific product specifications. In the semantic space exploration step, the Kansei words are gathered, expressing an emotion or a feeling through adjectives and grammatical forms.

Within the exploration of the property space, attributes and characteristics are selected, describing the product inside the chosen dominium. They are presented to the users as representative profiles. In the synthesis phase semantic and properties spaces are connected and correlated. The data are gathered within customers interviews and analyzed through several statistic techniques.

Then a validity test is conducted, in order to verify if explored spaces are coherent with the chosen dominium: if satisfying results are achieved, a model can be built, describing how properties and semantic space are correlated, otherwise a procedure reiteration is expected.

2. Application to case study

2.1 Dominium choice

The case study concerns all middle size motorcycles, with a displacement between 500 cc and 700 cc, belonging to the middle range touristic segment. The chosen target group is represented by all male population, older than 21 years: it is considered the minimum age threshold for driving a middle size motorcycle, with enough experience in usage for the specific case study product

2.2 Semantic space exploration

The Kansei words are nouns, adjectives or grammatical forms using whom it is possible describing the product. In order to get all the possible Kansei words, several sources have been investigated: motorcycles journals as *Motociclismo* or *Mototecnica;* experts; forum web pages; user interviews.

After a deep research 93 Kansei words have been selected. To avoid a very difficult questionnaire, a grouping of these words have been done by using an *affinity diagram* (Bergam and Klefsjö, 1994), thanks to the help of three medium-high culture subjects with the task of:

- Individually gathering the Kansei words;
- Discussing about individual work and kansei words placing;

- Giving labels to the different groups making higher level words;

After a careful analysis nine groups emerged as shown on Figure 2.

ORIGINAL	RELIABLE	ELEGANT (STYLISH)	COMFORTABLE
particular	solid	ambitious	practical
High Tech	resistant	luxurious	convenient
innovative	robust	sensational	ergonomic
original	reliable	elegant	light
modern	safety	brilliant	easy to drive
futuristic	compact	refined	comfortable
evolved	fragile	crude	cumbersome
alternative	stable	exclusive	voluminous
contemporary	balanced		silent
irregular	massive		edgy
bizarre	protective		
customizable	well-equipped		
personnel	durable	CLASSIC	
versatile		old-fashioned	
economic		traditional	
conventional		new serious	
		youthful look	

ESSENTIAL	ATTRACTIVE	ENERGETIC	AGILE
essential	pleasant	aggressive	dynamic
simple	admirable	wild	agile
minimal	attractive	energetic	snappy
functional	aesthetic	angry	handy
rough	nice	powerful	aerodynamic
technical	appealing	vigorous	fast
complex	charming	brutal	capable
challenging	exciting	extreme	heavy
	ellettrizante	bully	sporty
	dull	quiet	athletics
	extravagant	determined	
		aggressive	

Figure 2. Kansei words grouping with affinity diagram

2.3 Properties space exploration

The product properties space has been explored with a procedure similar to the one utilized for the semantic space: firstly all the product properties have been gathered through reading specialistic reviews, technical manuals, focus groups

The main issues for users have been selected from a list of 43 product characteristics. This task has been performed firstly from a three experts team, required of doing a starting screening and gathering properties depending on belonging, with five specific lists as output, plus an other general one, as shown in figure 3

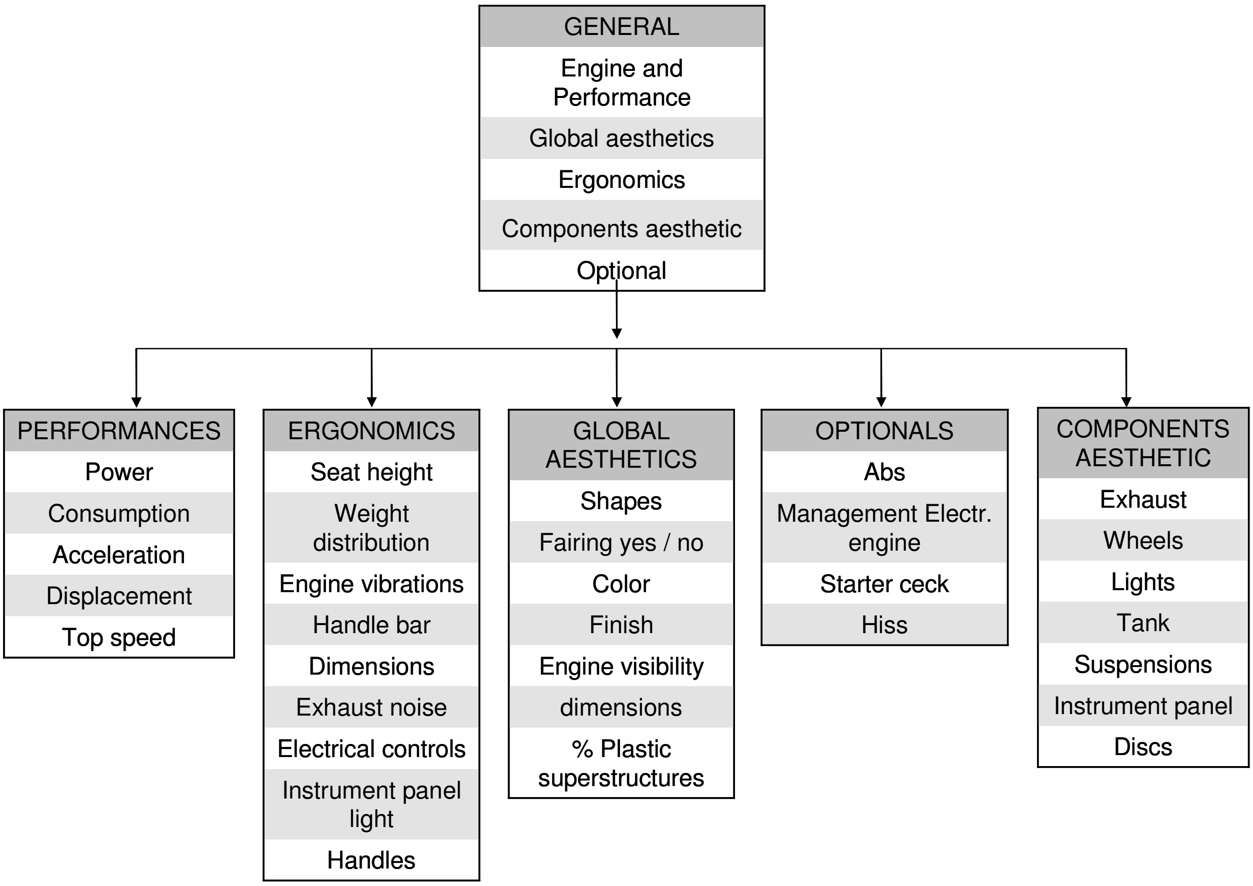
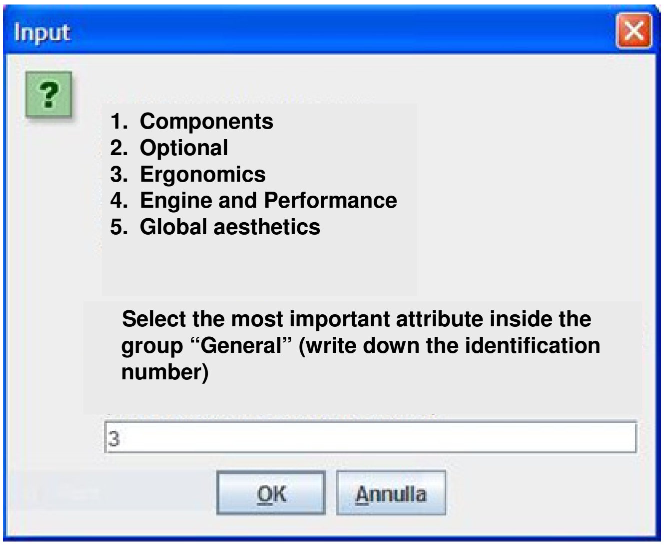


Figure 3. Attributes lists

A product properties evaluation has been done through several interviews with the objective of determining some design or component characteristics impact, for a middle size motorcycle, over respondents sensations and preferences.

The interviews have been conducted thanks to the help of the software ***Easy Attribute Weighing*** *(ESAW),* developed by Department of Technology, Production and Managerial Engineering (DTMPIG), of University of Palermo. The software is capable of understanding prior preferences of the respondents, not only by ranking attributes, but also depending on answering time. The questionnaire consists on ranking the attributes belonging to each list; step by step the respondent has to choose the preferred one among the remaining, until the end of the list.



1. Components
2. Optional
3. Ergonomics
4. Engine and Performance
5. Global aesthetics

Select the most important attribute inside the group “General” (write down the identification number)

3

Figure 4. ESAW, attributes classification window

The system output is an evaluation of the weights per each attribute with a six tables format report, one per each of the lists above introduced. Each list has a specific classification united to a distribution of normalized weights.

Table 1. ESAW: “general characteristics” list output

General characteristics	**Weight**	**Rank**
Engine and performance	0,41	1
Optional	0,41	2
Global aesthetic	0,104	3
Ergonomics	0,051	4
Components aesthetic	0,025	5

The product attribute rating has been done through gathering 41 interviews with motorcycle users within the specific age constraints. The final rating per each attribute “i” belonging to each list has been computed as the general sum of the corresponding software output weights.

$$W_{ij} = weight\ of\ "i"\ attribute\ for\ "j"\ respondent$$

$$W_{ij} = Rating\ "i"\ attribute = \sum_{j=1}^{J} w_{ij}$$

Six general areas lists, ranked by importance, have been drawn up, as shown on table 2, reporting the results of the interviews, useful to classify the attributes depending on the specific weight.

Table 2 Results from interviews for attributes ranking over importance weight

GENERAL	rating	ENGINE & PERFORMANCE	rating
Engine & Performance	14,754	Power	10,744
Global Aesthetic	8,609	Consumption	9,545
Ergonomics	7,769	Acceleration	7,204
Components aesthetic	5,82	Displacement	6,87
Optional	4,048	Top speed	6,637
GLOBAL AESTHETIC	**rating**	**GLOBAL AESTHETIC**	**rating**
Shapes	9,848	Exhaust	8,624
Fairings Y/N	8,331	Wheels	8,307
Colour	7,107	Lights	7,635
Finish	5,758	Tank	5,585
Engine visibility	4,45	Suspensions	4,542
Dimensions	4,075	Instrument panel	4,381
% plastic superstructure	1,431	Brake disks	1,926
ERGONOMICS	**rating**	**OPTIONAL**	**rating**
Seat high	6,793	ABS	14,409
Weight Distribution	6,496	Engine Electronic	10,8
Engine Vibration	6,417	Starting Ceck	8,564
Handlebar	5,477	HISS	7,227
Dimensions	5,43		
Exhaust Noise	4,25		
Electric Commands	3,002		
Instrument panel Light	1,626		
Handles	1,509		

The choice of attributes among the properties space for the matching with the semantic space, has to respect the final general rating as much as possible, but has also to take into account the real availability of real models for final interviews. Using these real models, with some variations, allows presenting several designs. The trade-off brought to a seven product attributes list, belonging to all the specific lists:

PERFORMANCES	GLOBAL AESTHETICS	COMPONENTS AESTHETIC	ERGONOMICS	OPTIONALS
Power	Fairing yes / no	Lights	Seat height	Abs
			Handle bar	
			Exhaust noise	

Figure 2. Selected product attributes

2.4 Product models selection through Design Of Experiments

Within the creation of the design of experiment, the product models to test have been selected. Under the hypothesis of no interaction between two control factors, a 2^{7-4} resolution III fractional plane made by eight trials (Montgomery, 2005) was chosen.

Table 3 shows in a clear way the chosen plane, while table 4 specifies the characteristics each model has to contain:

Table 3. Design of experiments

	Seat high	Fairings	Exhaust Noise	Handlebar	Lights	Power	ABS
Prototype 1	-	-	-	-	+	-	+
Prototype 2	+	-	-	+	-	-	-
Prototype 3	-	+	-	+	+	+	-
Prototype 4	+	+	-	-	-	+	+
Prototype 5	-	-	+	-	-	+	-
Prototype 6	+	-	+	+	+	+	+
Prototype 7	-	+	+	+	-	-	+
Prototype 8	+	+	+	-	+	-	-

Table 4. Control factor specification

N°	Factor	Level	Level label	Dimension
Factor 1	Power	-	Low	55 Cv
		+	High	75 Cv
Factor 2	Fairing	-	Yes	-
		+	No	-
Factor 3	Seat high	-	Low	776 mm
		+	High	796 mm
Factor 4	Handlebar	-	Chrome	
		+	Varnish	
Factor 5	Light	-	Double	
		+	Single	
Factor 6	Exhaust Noise	-	A	17 Hz[1]
		+	B	34 Hz
Factor 7	Abs	-	Yes	
		+	No	

The prototypes have been prepared as variants of some already existing models. This is the cheapest and simplest solution, despite inducing some noise factors, possibly affecting the results analysis. These noise factors can divided into two categories:

1. "Endogenous noise factors": product attributes to not test, affecting the evaluation of the respondent (e.g. Product colour).
2. "Halo effects": noise factors affecting customer perception for product attributes (e.g. product brand) [7] [8].

Thanks to a new methodology of experimental study applicable in Kansei Engineering and conjoint analysis, we can filter these noise factors through the amplification of input signal.

The procedure shall aim to estimate how much a specific attribute is important for the respondent, and while achieved, it is utilized as corrective factor in the logistic regression (see figure 6).

---

[1] The exhaust noise has been computed by considering the harmonic content of main frequencies for a our stroke engine with two or four cylinders @ 1000 rounds per minute (17Hz and 34Hz).

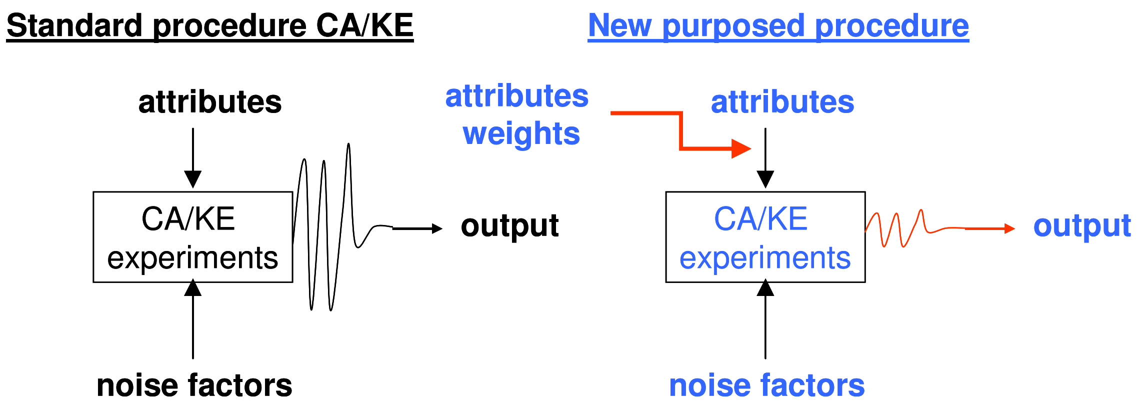


Figure 3 standard procedure and new methodology for CA/KE experiments

2.5 Synthesis phase

In this phase the interaction between semantic and property space has been investigated through interviews conducted with a customers target sample. As explained on previous paragraph the synthesis interview is divided into two parts:

1. Weight attributes evaluation.
2. Kansei Engineering Interview.

First part follows the framework of first interviews series, and it is utilized to estimate how a specific attribute is important for the respondent. The attributes here mentioned are the same of previous section, dialing the Design Of Experiments. The interviews have been again conducted with the help of the software *EaSy Attribute Weighing (ESAW).*

The second part consists of a motorcycle static trial. During the test a reproduction of the required exhaust sounds is submitted to the respondent with headphones (figure 8). At the end of the trial the respondents are required to describe the prototypes, concerning each Kansei words meaning, by giving an evaluation through a semantic scale on a paper questionnaire (Osgood, 1969) [10] (appendix 1).

Figure 4 motorcycle prototype static trial

2.6 Results analysis

The analysis of results has been performed with a logistic ordinal regression, whose aim was to quantify the relation between the customer Kansei, expressed by words, and product attributes. Per each Kansei word a model has been created where the score of the semantic scale has been utilized as dependent variable, while the D.O.E. attributes are considered as input (or independent) variables. The output data have been analyzed through statistic software MINITAB.

Table 5 weighted ordinal logistic regression output

Product attributes	**Level 1 vs. Level 0**	**Coefficient**	**SE Coefficient**	**P value**	**Odds Ratio**	**Confidence Interval 95%**	
						Lower	**Upper**
KANSEI WORD: RELIABLE							
Power	High (vs.Low)	0,290561	0,813003	0,721	1,34	0,27	6,58
Fairing	No (vs. Yes)	-1,49862	1,17724	0,203	0,22	0,02	2,25
Seat High	High (vs.Low)	0,182239	1,08905	0,867	1,2	0,14	10,14
Handlebar	Chrome (vs. Varnish)	0,352011	1,44476	0,525	2,51	0,15	42,55
Lights	Mono (vs. Double)	-3,05011	1,39806	0,029	0,05	0,00	0,73
Exhaust Noise	4cyl. (vs. 2cyl.)	3,68069	1,28414	0,004	39,67	3,2	491,56
ABS	Yes (vs. No)	-2,60848	1,51445	0,005	0,07	0,00	1,43

The significative product attributes are highlighted for being characterized by a p-value lower than 5% (0,05): their correspondent logit coefficients quantify the relation between product attribute level variation and a specific kansei word (in this case "RELIABLE").

Information concerning the model validity come from G-test, measuring the ordinal logistic regression optimality. Stepping from this value it is possible to evaluate the significance of the coefficients associated to the regressors through the p-value, verifying the hypothesis of all being zero, against the alternative of at least one being different from zero. On table 6 per each kansei words within the weighted model, G-test and P-values are indicated: the models are significative being p-value lower than 5%.

Table 6 G-test and P value per each kansei word on weighted model

Weighted model	**Original**	**Reliable**	**Elegant**	**Classic**	**Comfortable**	**Essential**	**Attractive**	**Energetic**	**Agile**
G-TEST	37,98	39,308	51,88	58,627	43,714	66,295	52,858	56,656	54,927
P-value	0,002	0,001	0,000	0,008	0,001	0,000	0,001	0,000	0,000

2.7 Case study Conclusions

Established the connection between product characteristics and Kansei words, it is elicited suggesting which specific attribute produces a particular emotion or feeling in a potential customer and which is the emotion level. The logistic regression analysis reveals that there are several elements influencing the respondent impressions, and significative regressors (in absolute value) are explained on summarizing table 7:

Table 7 Weighted Logistic ordinal regression output – quantitative table

Weighted Model	**Power**		**Fairing**		**Seat High**		**Handlebar**		**Lights**		**Noise**		**Abs**	
	High	Low	Yes	No	High	Low	Varnish	Chrome	Mono	Double	A	B	Yes	No
Original				0,65										
Reliable									3,05			3,68	2,61	
Elegant	1,47							3,55						
Classic				0,48					0,84			2,08		
Comfortable						2,54						2,67		
Essential				4,81								3,61		
Attractive	1,40			1,29										
Energetic	1,22			2,36										
Agile				4,40										

Now is possible building a qualitative table using the signals:

- +++ factors highly inluencing Kansey word (coefficient higher than 3);
- ++ factors medium inluencing Kansey word (coefficient higher between 1,5 and 3);
- + factors mildly inluencing Kansey word (coefficient lower than 1,5

Table 8 Weighted Logistic ordinal regression output – qualitative table

Weighted Model	**Power**		**Fairing**		**Seat High**		**Handlebar**		**Lights**		**Noise**		**Abs**	
	High	Low	Yes	No	High	Low	Varnish	Chrome	Mono	Double	A	B	Yes	No
Original				+										
Reliable									+++			+++	++	
Elegant	+							+++						
Classic				+					+			++		
Comfortable						++						++		
Essential				+++								+++		
Attractive	+			+										
Energetic	+			++										
Agile				+++										

Considering data within details, it is possible to say that:

- An high power has light influence on words like “elegant” , “actractive” or “energetic”: the last one can be justified by thinking the customers associates an “energy increasing” as well as engine power increases;

- The absence of fairing influences the most of Kansei words: “original”, “classic”, attractive”, “energetic” and especially “essential” and “agile”. It’s easy understanding the connection with “essential”, since the absence of fairing recalls the idea of a *naked* motorcycle, essential by definition;

- The connection with the word “agile” is instead hard to understand: the fairing is an aerodynamic equipment useful to reduce aerodynamic resistance, nevertheless the respondents feel more like “agile” within the fairing absence. This result can be justified thinking the analysis is done on a touristic motorcycle dominium, where fairings don’t reflect exactly the idea of agility, as well as it occurs within the super-sport segment. Moreover it is compulsory remember that the study concerns emotions and feeling, not influenced by a functional analysis on components: then sometimes unexpected results can arise;

- A low seat has a positive influence on comfort rather than a high one, because lowering some centimetre the seat is possible appreciate how lower limbs joint angles are reduced, in particular on knees: it gives a feeling of relief;

- An easy reading concerns the correlation between chrome handlebar and feeling of “elegance”, as results from interviews: while in light the chromium plating returns a shimmering effect giving a certain charm and sophistication;

- Concerning lights a mildly correlation between mono light and the word “classic”: the most of vintage motorcycle has a single light while double one equips the more recent models. But more interesting is the strong correlation between Kansei word “reliable” and mono light property: the presence of a single light could give the sensation of something compact and more resistant, returning the idea of reliability;

- The exhaust noise (A), generated by a twin (two cylinders) engine, is associated to high scale values for words like “reliable”, “classic”, “comfortable” and “essential” within the comparison with (B) sound, generated by a four cylinders engine, more performing and elaborate, much less recalling classic and essential motorcycles;

- Finally an obvious interpretation arises looking at the strong correlation between presence of ABS and growing reliability feeling, since the customer knows the safety benefits connected with shortening the braking distance;

3. Conclusions

This paper shows the potentiality of Kansei Engineering, trying to identify the impact of different product attributes levels, in a middle size touring motorcycle, on customers perceptions, but the same procedure could be adopted to improve any kind of product. Despite some positive results have been achieved, a collaboration with a manufacturer within the sector could help the analyst understanding the problems emerging during the study, like the possibility of fitting out prototypes fully reflecting the design of experiment, able to evoke particular feelings linked to Kansei words.

The arising results could be utilized from manufacturing companies to develop new market strategies. For example a motorcycle producer could focus from this study the levers where conveniently operate in terms of product attributes to bring out certain sensations on potential customers, to place the product inside a specific market segment, or rather well addressing the communication campaign for a product already placed in the right market niche. An other use could be suggested by the correlation evaluation method, where the sensation arising is connected with the attribute level changing. The idea could be: “there is no feeling without level properties plurality”. Then Kansey Engineering could help on optional setting in order to better handle the impact of prices on different preparations.

Kansey Engineering is an instrument which utilizing a systematic procedure and statistic analysis methodologies, allows identifying concrete project solutions based on sensations and *not declared expectation of customers*. For there reasons it arises as innovative tool using whom it is possible to get a real advantage over market competitors.

Appendix 1

How do you evaluate this prototype respect these Kansei words?

Kansei words	Very low	Low	Medium	Very	Very much
ORIGINAL	☐	☐	☐	☐	☐
RELIABLE	☐	☐	☐	☐	☐
ELEGANT	☐	☐	☐	☐	☐
CLASSIC	☐	☐	☐	☐	☐
COMFORTABLE	☐	☐	☐	☐	☐
ESSENTIAL	☐	☐	☐	☐	☐
ATTRCTIVE	☐	☐	☐	☐	☐
ENERGIC	☐	☐	☐	☐	☐
AGILE	☐	☐	☐	☐	☐

References

[1] Nagamachi, M. (1989). Kansei Engineering. Kaibundo, Tokyo

[2] Stefano Barone, Alberto Lombardo, Pietro Tarantino (2005). A Weighted Ordinal Logistic Regression for Conjoint Analysis and Kansei Engineering Experiments. Università degli studi di Palermo.

[3] Schutte, S.T.W., (2002). Designing feeling into products integrating Kansei Engineering methodology in product development. Institute of Technology, Linkoping

[4] Barone, Lombardo, Tarantino (2007). A Heuristic Method for Estimating the Attribute Importance by Measuring the Choise Time in a Ranking Task. Università degli studi di Palermo.

[5] Bergman, B.,Klefsjo¨, B. (1994). Quality: from customer needs to customer satisfaction. Lund, Sweden: Studentlitteratur

[6] Montgomery, D.C.(2005). Design of Experiments. 5th Edition. McGraw-Hill

[7] Lance, C.E. and Woehr, D.J. (1986). Statistical Control of Halo: Clarification From two Cognitive Models of the Performance Appraisal Process. Journal of Applied Psychology 71(4), 679-685.

[8] Murphy, K.R. et al. (1993). Nature and Consequence of Halo Error: A Critical Analysis. Journal of Applied Psychology78(2), 218-225.

[9] Hosmer, D.W. and Lemeshow, S. (2000). Applied Logistic Regression. John Wiley & Sons. New York, 2nd Edition

[10] Osgood,C.E. et al. (1969). The Measurement of Meaning. In: Semantic Differential Technique- a source Book, Aldine publishing company, Chicago, pp 56-82

Chapter 4

Robust dynamic comfort modelling for motorcycle riding

Submitted

Robust dynamic comfort modelling for motorcycle riding

Stefano Barone & Giovanni Lo Iacono
University of Palermo, Italy

These days, comfort modelling is considered a prerequisite in motorcycle design, primarily to address safety concerns and to position the product on the market. However, a comprehensive methodology for comfort modelling during the earliest development phases of a new motorcycle model is still missing.
Anthropometrical variation is the main noise factor to consider in comfort modelling in relation to unavoidable variability of body segments. However, comfort is a subjective concept, and can influence riders' choice of motorcycle model.

This work is a generalisation of the Robust Ergonomic Design methodology aimed at designing products whose ergonomic performance is insensitive to anthropometrical variation. This work further develops the methodology by considering the dynamic aspects involved in the driver–motorcycle interaction.
This work defines a generalised robustness criterion and presents a full simulation study using purposely developed software.

Keywords: Robust Design; Ergonomics; Comfort assessment; Motorcycle design; Human modelling; Man–machine interaction; Digital mock-up.

1. Introduction

These days, when machines are increasingly required to adapt to human beings, more than the other way around, designers take ergonomics very seriously with the intention of improving safety and user satisfaction. This area of research is called "micro-ergonomics" and focuses on the improvement in workspaces and on the design of man–machine interfaces to prevent daily life risks. In the automotive field, ergonomics is well known to be related to driving safety (Noy 1997). Ergonomic design involves three main aspects: anthropometrics, physiology, and cognitive psychology. For example, for the design of a workstation, some prescriptions are (Gilad & Karni 1997; Wilson 2000):

- Avoid static work environment conditions;
- Variety better than variation;
- Right lighting, seat, desk, and view;
- Instruments very intelligible by the user.

Another example is the investigation of the relationship between the height adjustment of bed sectors and body comfort in sleeping positions (Park, Kim and Kim 2009).

Machine manufacturers must predict the comfort feeling in the early phases of the design process, especially in the automotive sector, given the high cost of developing mock-ups. This point also applies to motorcycles and the central role of driver posture, even though creating mock-ups is not as expensive as in the automotive sector.

Virtual environment software such as *Jack*® (Collins *et al.* 1990) and *Ramsis*® (Vogt *et al.* 2005) facilitate posture prediction based on the angles between the body segments, because such angles are related to the feeling of comfort (Porter & Gyi 1998, Barone & Curcio 2004).

The use of digital manikins is today a standard practice to analyse the interface between driver and vehicle (Chung & Park, 2004).

Motorcycle design should consider the fact that few adjustments to improve comfort are allowed to the rider, given that the link between user and motorcycle must be very stiff.

The literature on anthropometric data of motorcycle riders is very limited. Robertson and Minter (1996) highlighted the fact that motorcycle riders are taller than average, possibly the result of seat height. Their study was based on a sample that included 109 male and 31 female volunteers, all motorcycle riders. Stature and body segment measurements were taken. Chou and Hsiao (2005) proposed a methodology for measuring and analysing the anthropometric characteristics of scooter riders and, consequently, formulating a design proposal for a new scooter model.

This work considers the gap between the subjective comfort feeling and the objective best layout. Obviously, the greater importance that is given to the former, defining the latter becomes less important.

As mentioned above, the human comfort feeling is based on physiological considerations as well as psychological aspects, which are more difficult to measure and consider in the design process. Some work on this subject refers to the Kansei Engineering research area (see, for example, Nagamachi 1989; Barone, Lombardo and Tarantino, 2007; Barone, Lo Iacono and Pampinella 2010).

If the comfort feeling is a prerequisite for user safety and product positioning in the market, a motorcycle must ensure high comfort in any operating condition.

For example, a racetrack motorcycle compels a driver to align his or her arms as much as possible with the forks to impress the right rolling force for turning, without generating a steering component on the handlebar. Conversely, a scooter driver must have freedom on lateral movements when turning; therefore, the scooter footboard is designed to guarantee that the driver sits in a forward position on the seat.

Comfort needs not necessarily be high, but should be coherent with the target of the motorcycle.

This paper extends the already proposed Robust Ergonomic Design methodology (Barone & Lanzotti 2002; 2007; 2008). The novel idea proposed in the present work is to design products whose ergonomic performance is not only insensitive to the unavoidable anthropometrical variation, but that also spouse the dynamic man–machine interaction, aiming to find a trade-off between driver feeling and performance.

The integration of dynamic situations in an ergonomics study is not new in the literature. For example Chang & Wang (2007) calculate the compression and shear forces on the intervertebral disk (related to physical discomfort) from the moments generated by external forces in a generic workstation.

As a final result of our work, the evaluation of an optimal driving posture can be done by involving forces, moments, and energy. A robustness criterion (generalised dynamic comfort loss function) is finally formulated and adopted.

The article has the following structure. Section 2 clarifies the research questions and the objectives of this work. Section 3 describes the robust dynamic comfort methodology as a significant evolution of previously developed work. Section 4 presents the purposely developed software and an example of application of the methodology. Section 5 provides the conclusions and delineates opportunities for further research work.

2. Research questions and objectives

Simply taken, the joint angles (Porter & Gyi 1998) are not the only possible way to obtain an objective evaluation of comfort. For example, Barone and Curcio 2004 used vibrations in addition to joint angles. Another possible way is to rely on the use of forces and pressures acting on the interface between the product and the user (see, for example, Bubb & Estermann 2000). Based on previous research and considering that the issue is not exhaustively solved, the present paper considers the role played by moments in the main articulations, in addition to joint angles.

Consider the natural posture that a human assumes in the absence of gravity. Some studies on astronauts (Motta & Bordone 2003) showed that during the first month in orbit astronauts start retreating the bottom backwards to keep control on the barycentre (to be sure not to fall on their face). They take a posture that can be viewed as close to a “neutral” one (see section 3). This behaviour is indicative of a feedback control, where bottom retreating is the first solution instinctively found. After a while, astronauts return to a natural “normal gravity” position, with the barycentre projection located between foot fingers and heel, the best solution to maximise walking speed and stability in all voluntary actions. The movement forces are the results of gravity and moments at the joints, especially in the ankle: since both can increase the friction force on the ground, the articular forces need to be higher at lower gravity. Therefore, after about three months in orbit, the final posture of the astronauts is more tilted forward. This behaviour involves a feed-forward control, since the astronauts do not stop at the first solution in search of equilibrium and, despite certain equilibrium loss, attempt for a higher walking performance level while continuously improving the posture performance. The higher the comfort loss – leaving the neutral position – the higher the performance.

For motorcycle riders, we assume a dual perspective with respect to astronauts. In fact, for motorcycle riders, changing posture is impossible: the more accustomed they get to driving, the more gladly they accept some loss of comfort. When a scooter driver rides a racetrack motorcycle for the first time, he/she feels high discomfort. With the passage of time, he/she feels less discomfort and increasing driving pleasure.

Our aim is to provide a general methodology for modelling the comfort perception in both static and dynamic situations during the early design phases of a new motorcycle model, and to look for the optimal comfort setting.

Some specific goals include:

- Integration between concept design and comfort modelling prior to building a mock-up;
- Easy management of anthropometric peculiarities;
- Realistic comfort modelling based on dynamic simulation.

Figure 1 shows a conceptual map of the work. The Robust Dynamic Comfort in motorcycle riding is obtained by considering both driver and motorcycle as two objects to undergo both a design phase and a usage (cognitive) phase, where driving skills and dynamic characteristics of the machine are involved.

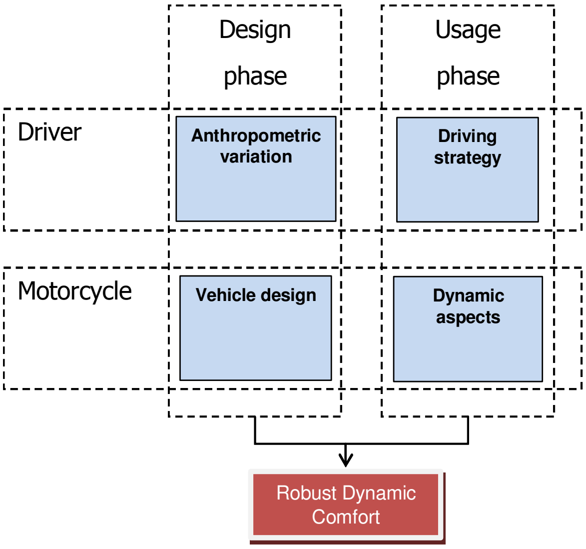


Figure 1. Conceptual map of robust dynamic comfort modelling.

3. Robust dynamic comfort modelling

For motorcycle engineering design, robust dynamic comfort modelling is a methodology specifically thought to improve new models under development by making comfort performance as insensitive as possible to sources of variation in usage. In Robust Design terminology (Andersson 1997; Hasenkamp, Arvidsson and Gremyr 2009), these are called noise factors.

Dealing with anthropometrical variation

The most significant noise factor to consider is the variation of anthropometric dimensions characterising the target population. Anthropometric features affect the joint angles, which are strongly related to comfort (Porter and Gyi, 1998). This aspect is highly penalising in motorcycle design because very little adjustments or regulations are possible for the user. Designers should take this aspect into account from the early development phases.

Barone and Lanzotti (2002) formulated a multivariate loss function as a comfort performance index. For each joint angle, the adopted loss function model is the quadratic asymmetric:

$$L_j = L\left[Y_j(H)\right] = \begin{cases} \alpha_j\left[Y_j(H)-\tau_j\right]^2 & \text{if} \quad Y_j(H)\le\tau_j \\ \beta_j\left[Y_j(H)-\tau_j\right]^2 & \text{if} \quad Y_j(H)>\tau_j \end{cases} \qquad j=1,\dots,J \qquad (1)$$

where:

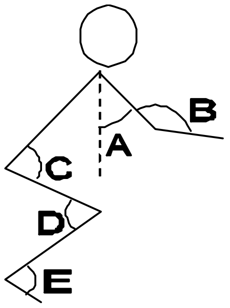
L_j is the comfort loss for the *j*-th joint angle. *J* is the number of joint angles considered in the study (*J* = 5 in Table 1);

Y_j is the joint angle value. It is a random variable due to the variation of body height *H* and well surrogates the variation of body segments (Reed and Flanagan, 2000);

τ_j is the preferred value for each joint angle, according to Porter and Gyi (1998), see Table 1;

$\alpha_j = \left(y_{j,\min}-\tau_j\right)^{-2}$ and $\beta_j = \left(y_{j,\max}-\tau_j\right)^{-2}$, where $y_{j,\min}$ and $y_{j,\max}$ are, respectively, the minimum and the maximum joint angle values found by Porter and Gyi.

Table 1. Minimum, preferred and maximum value of joint angles (adapted from: Porter and Gyi 1998). Loss function model coefficients α and β.

Joint angle Y_j	min $y_{j,\min}$	preferred τ_j	max $y_{j,\max}$	α_j	β_j	
A Upper arm flexion	19	50	75	0.00104	0.00160	
B Elbow angle	86	128	164	0.00057	0.00077	
C Trunk-thigh angle	90	101	115	0.00826	0.00510	
D Knee angle	99	121	136	0.00207	0.00444	
E Foot-calf angle	80	93	113	0.00592	0.00250	

Summing up the losses for each of the considered joint angles provides a total loss:

$$L_{tot}(H) = \sum_{j=1}^{J} L_j \tag{2}$$

The expected value of the total loss is:

$$E\{L_{tot}(H)\} = \int L_{tot}(H) \cdot f_H(h)\,dh \tag{3}$$

where $f_H(h)$ is the probability density function of the body height H.

Note that, regardless of the correlation structure of joint angles:

$$E\{L_{tot}(H)\} = \sum_{j=1}^{J} E\{L_j\} \tag{4}$$

The expected comfort loss has been used as a performance index in several applications in combination with design of experiments performed in a virtual environment (Barone and Lanzotti, 2002, 2009).

Barone & Lanzotti (2007) showed in practice that it is possible to replace the continuous probability distribution of body height with a discrete approximation grounded on selected "percentiles" of the population.

However, if the target population is a mix of males and females (as in most cases), the probability density function of the body height is a mixture:

$$f_H(h) = k \cdot f_w(h) + (1-k) \cdot f_m(h) \tag{5}$$

where k is the so-called mix coefficient (namely, proportion of females in the mixture).

It has been demonstrated that, in order to achieve the equivalence between the two probability distributions (the continuous mixture and its discrete approximation), it is possible to equate the first three absolute moments of the two distributions. Furthermore, the necessary constraint on the sum of probabilities for the discrete r.v. is imposed, which leads to the following system of equations:

$$\begin{cases} k\mu_w + (1-k)\mu_m = \sum_{i=1}^{4} h_i w_i \\ k\left(\sigma_w^2 + \mu_w^2\right) + (1-k)\left(\sigma_m^2 + \mu_m^2\right) = \sum_{i=1}^{4} h_i^2 w_i \\ k\left(\mu_w^3 + 3\mu_w\sigma_w^2\right) + (1-k)\left(\mu_m^3 + 3\mu_m\sigma_m^2\right) = \sum_{i=1}^{4} h_i^3 w_i \\ \sum_{i=1}^{4} w_i = 1 \end{cases} \tag{6}$$

where:

w_i ($i = 1,...,4$) is the unknown probability mass (weight) concentrated at h_i;

h_1 is the fifth percentile of H_w (female height distribution);

h_2 is the 50th percentile of H_w;

h_3 is the 50th percentile of H_m (male height distribution);

h_4 is the 95th percentile of H_m.

Once the continuous height distribution is replaced with its discrete approximation, the expected total loss can be calculated by:

$$E\{L_{tot}\} = \sum_{j=1}^{J} \sum_{i=1}^{4} l_{ji} w_i \tag{7}$$

where l_{ji} is the loss of the i-th percentile in terms of j-th joint angle.

Introducing dynamic aspects: the concept of neutral posture and the load factor

The formulated loss function model (1) based on Porter and Gyi's (1998) joint angles refers to a posture in a normal gravity situation with underlying static forces. For this reason, we henceforth denote that loss by $L_{j,\mathrm{static}}$.

To increase the generality of the loss function model using forces and moments that are not necessarily static is advisable.

Accordingly, a dynamic loss is defined:

$$L_{j,dynamic} = L_{j,static} \frac{M_{j,dynamic}}{M_{j,static}} \tag{8}$$

where:

$M_{j,\mathrm{dynamic}}$ is the moment module at the *j*-th joint calculated in correspondence to a specific dynamic situation;

$M_{j,\mathrm{neutral}}$ is the moment module at the *j*-th joint calculated in correspondence to Porter and Gyi's preferred posture, which is assumed as a *neutral* posture.

The neutral posture can be considered as a state of hydrostatic equilibrium. With reference to the explanation in Section 2, the neutral posture is an unconstrained posture that is naturally assumed in zero gravity conditions, for example.

Figure 2 illustrates the conceptual steps described previously: a neutral zero-gravity posture; posture design in product development; and final outcome of a carefully studied posture design.

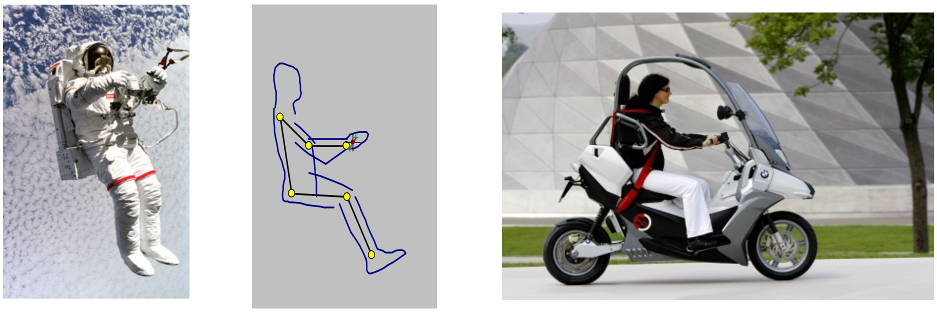
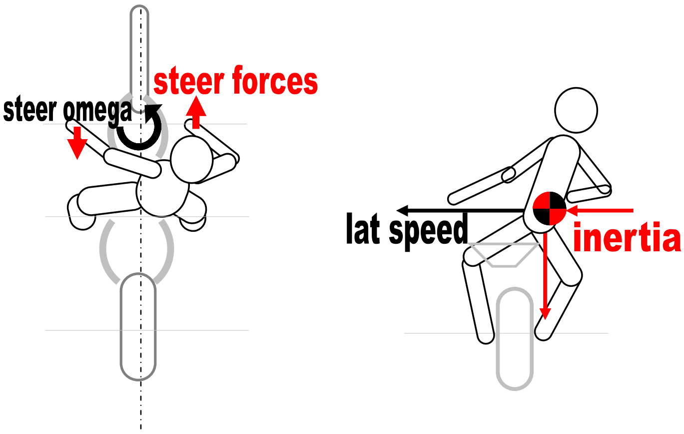


Figure 2. Illustrated concept of neutral postures.

The rationale of formula (8) is to consider the neutral posture as a reference to normalise any dynamic situation: by resetting the stress levels, and then charging the articulations with the related dynamic load. The ratio between the moments in (8) is denoted by "*load factor*".

The energy factor

The energy factor is a dimensionless index of the energy that a motorcycle rider spends on a simulated driving test. Neglecting friction and the pressure between body and motorcycle seat, which are out of the scope of this work, we assume that the rider spends energy in two possible ways (see Figure 3): for the steering rotation (*a*); for shifting his/her barycentre to obtain the rolling equilibrium (*b*).



(a) **(b)**

Figure 3. Scheme of the forces for the calculation of the energy factor.

The steering rotation energy is given by:

$$E_{steering} = \int_0^{s_f} T_{steering}(s)\ \omega_{steering}(s) \frac{ds}{v(s)} \tag{9}$$

where:

s is the covered distance, s_f is the overall distance of the driving test;

$T_{steering}(s)$ is the steering torque;

$\omega_{steering}(s)$ is the steering angular speed;

$v(s)$ is the highest possible calculated motorcycle speed in the simulated test path based on friction constraints.

The driver barycentre movement, a feedback movement to obtain an instantaneous rolling equilibrium, implies the energy:

$$E_{barycenter} = \int_0^{s_f} m \cdot A_y(s) \cdot v_y(s) \frac{ds}{v(s)} \tag{10}$$

where:

m is the driver's mass;

$A_y(s)$ is the transverse apparent acceleration against which the driver moves;

$v_y(s)$ is the lateral relative speed of body movement (see Figure 3).

Once the energies are calculated, we define the dimensionless energy factor as the ratio:

$$E_f = \frac{\left[E_{steering} + E_{barycenter}\right]}{mgh} \tag{11}$$

where g is gravity acceleration and h is driver height; therefore, mgh is the driver potential energy, considered a reference term. The energy factor is taken into account into the generalised comfort loss function according to the following formula:

$$L_{generalized} = L_{dynamic} \cdot E_f \tag{12}$$

Upon defining the generalised comfort loss according to (12), its practical calculation following (7) is given by:

$$E\left\{L_{tot,generalized}\right\}=\sum_{i=1}^{4}w_iE_{f,i}\sum_{j=1}^{J}L_{dynamic,ij} \qquad (13)$$

4. An example of application using dedicated software

Software purposely developed in Visual Basic allows human body modelling and dynamic comfort calculation for any motorcycle prototype, also purposely digitalised. For human body modelling, the anthropometric data provided by Greil (1988) were adopted (Table 2).

Using the sample data of Robertson and Minter (1996) to calculate the mix coefficient k (see (5), section 3) and the anthropometric data of (Table 2), the solution to equation (6) gives: w_1=0.02; w_2=0.34; w_3=0.45; w_4=0.18.

Table 2. European population anthropometric data (source: Greil 1988).

Anthropometric characteristics (mm)	5th female	50th female	50th male	95th male
Height	1510	1610	1733	1841
Shoulders	1230	1339	1445	1542
Groin	670	720	816	886
Horizontal action radius (operating hand axis)	616	690	722	787
Eyes level height	1402	1502	1613	1721
Vertical action radius (operating hand axis)	1748	1870	2051	2210
Pelvis width (up standing)	314	358	344	368
Hand axis height	664	738	767	828
Weight	41.00	51.00	73.30	84.10

Preliminary simulations with the software permitted validation of the assumption that body height is a good surrogate for anthropometric variation. In other words, by changing body height, all parametrically scaled features were in accordance with the percentiles of Table 2.

Errore. L'origine riferimento non è stata trovata. shows the 3D model of a human body made of joints and skin surface generated by the software. The bullets are the joints, and their positions parametrically vary depending on the chosen body set (a specific combination of anthropometric characteristics).

Errore. L'origine riferimento non è stata trovata. illustrates the schemes for calculating the moments defined in (8).

A motorcycle prototype imposes handlebar grips, a footboard and a saddle as constraints for the driver. Based on that, all joint angles can be measured.

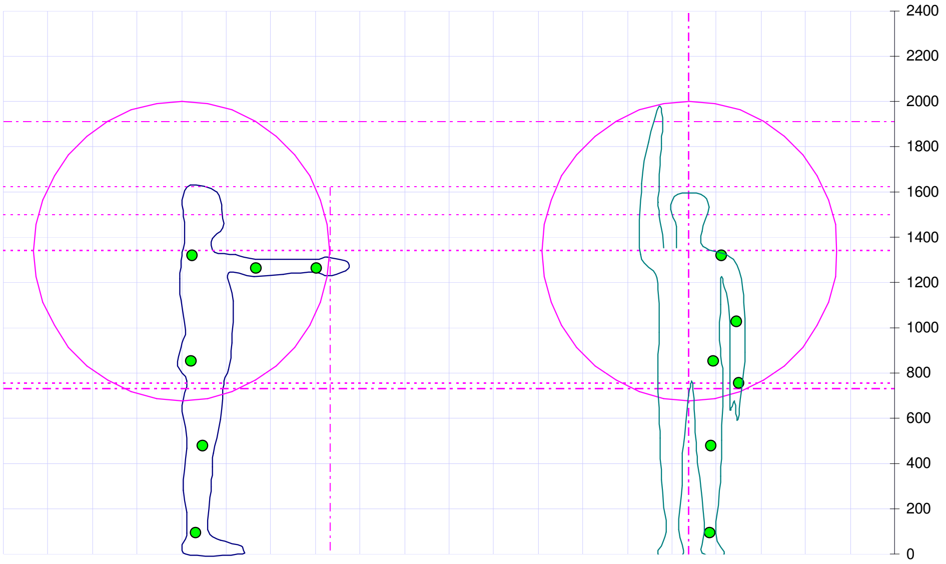


Figure 4. Example of the anthropometric body model, with joints (bullets) and skin, in the purposely developed software. The circles are based on the radius of action.

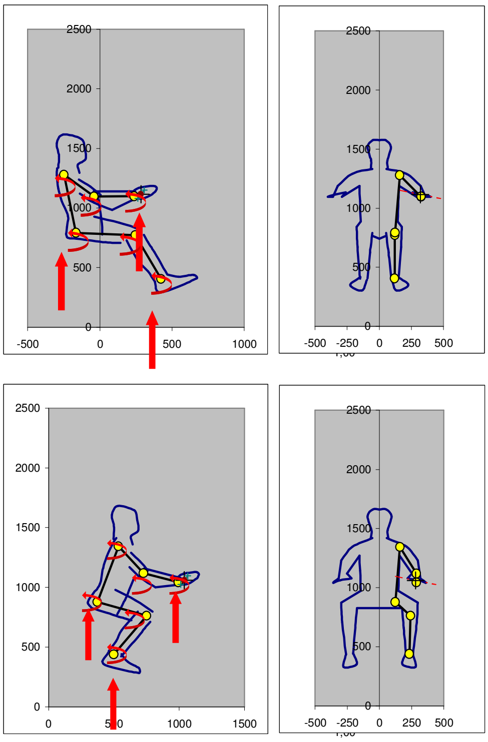


Figure 5. Schemes for calculating $M_{neutral}$ and $M_{dynamic}$. Indication of normal reactions and joint moments.

Figure 6 shows the static loss functions $L_{j,static}$ for each considered joint angle and body set (5th, 50th female and 50th, 95th male percentiles) for a specific chosen motorcycle prototype (maxi-scooter, see Figure 8), and the loss functions are calculated according to (1). Note that the loss values differ depending on the considered joint angle (see the scales for the vertical axes).

The chosen motorcycle prototype imposes a posture similar to an automotive one, explaining why the static losses are so close to zero, except for the extreme percentiles (5th female and 95th male).

Figure 7 shows the dynamic losses calculated by (8) for the same body sets and motorcycle prototype of Figure 6. We can observe that the points no longer lie on the curves (dynamic losses can be either higher or lower than static losses). Table 3 gives the load factors calculated for the selected motorcycle prototype.

Figure 8 shows part of the maxi-scooter prototype design matching a specific body set (50th percentile male).

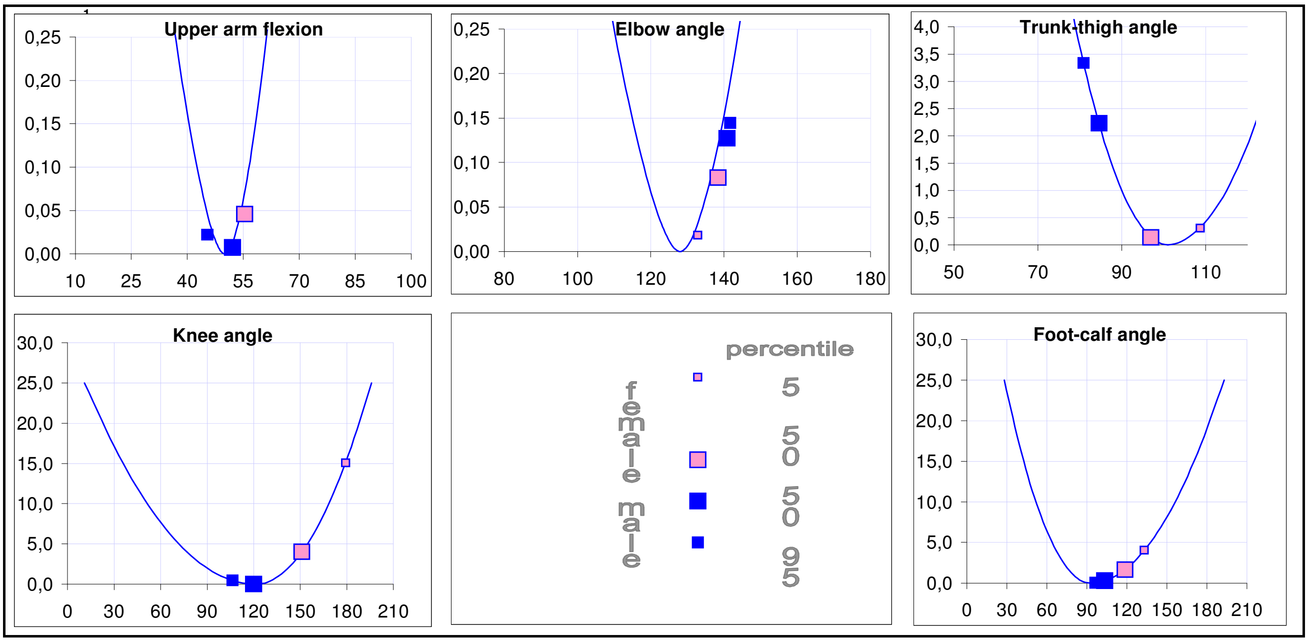


Figure 6. Joint angle static losses $L_{j,static}$ (four body sets) for a maxi-scooter prototype.

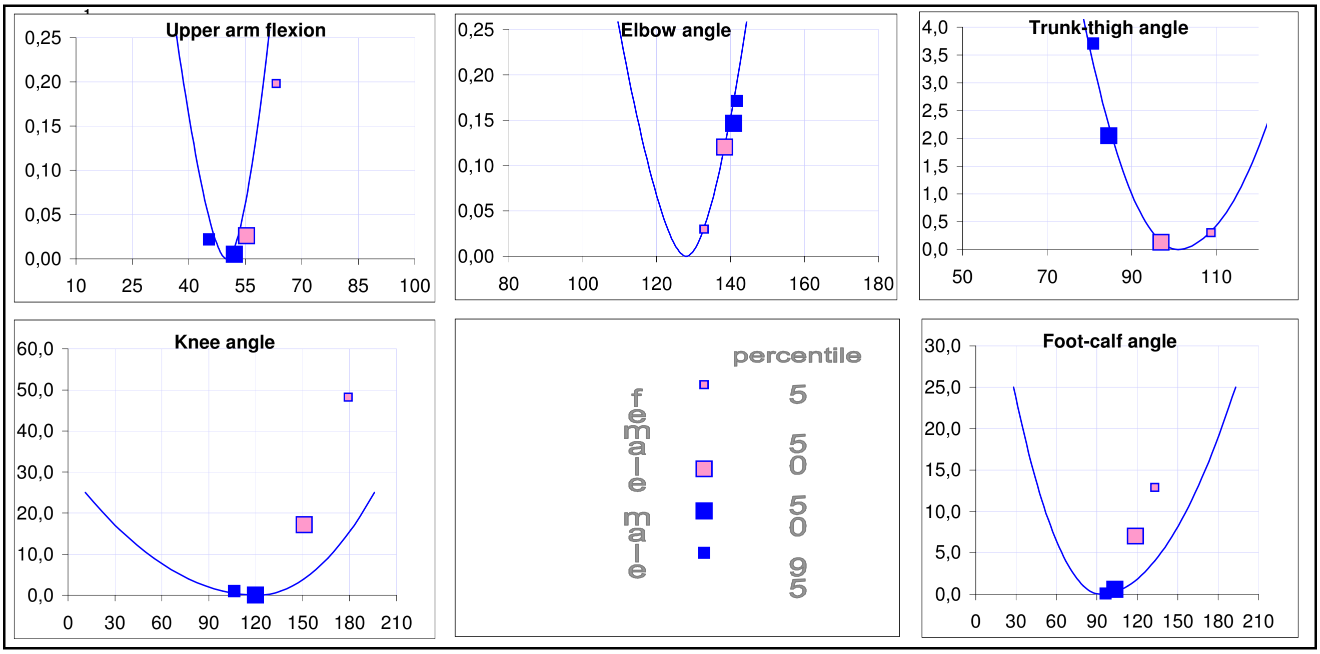
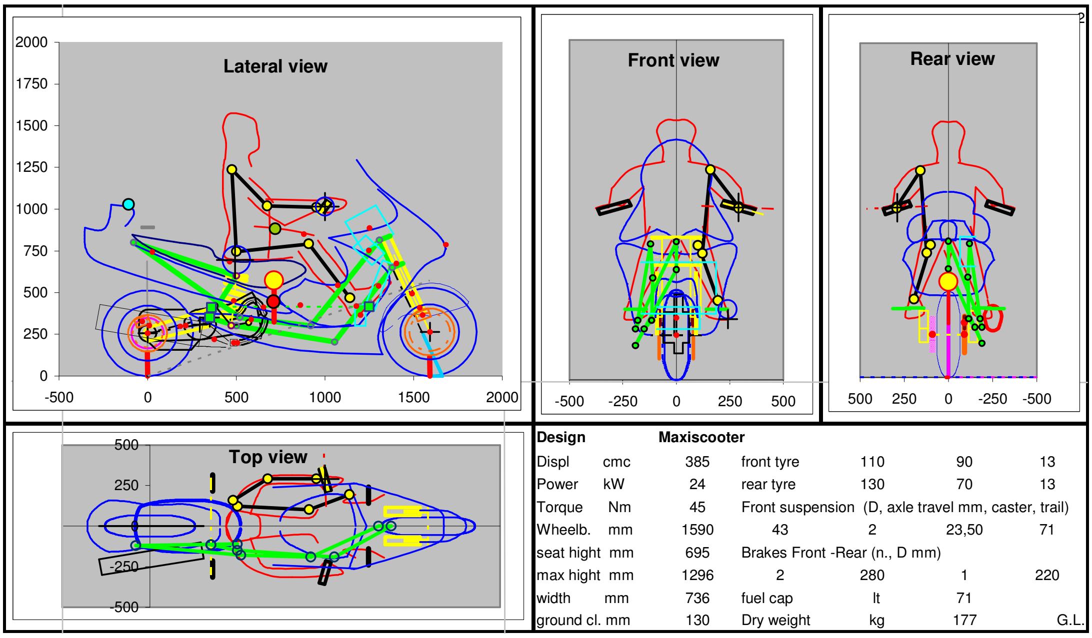


Figure 7. Joint angle dynamic losses $L_{j,dynamic}$ (same body sets and motorcycle prototype of Figure 6).

Table 3. Load factors for the four body sets (5th, 50th female, 50th, 95th male percentiles) and maxi-scooter motorcycle prototype.

Body set / Joint angle	5th female	50th female	50th male	95th male
Upper arm flexion	0.7	0.6	0.7	1.0
Elbow angle	1.6	1.5	1.2	1.2
Trunk-thigh angle	1.0	1.0	0.9	1.1
Knee angle	3.2	4.3	2.2	2.2
Foot-calf angle	3.2	4.3	2.2	2.2



Design		**Maxiscooter**				
Displ	cmc	385	front tyre	110	90	13
Power	kW	24	rear tyre	130	70	13
Torque	Nm	45	Front suspension (D, axle travel mm, caster, trail)			
Wheelb.	mm	1590	43	2	23,50	71
seat hight	mm	695	Brakes Front -Rear (n., D mm)			
max hight	mm	1296	2	280	1	220
width	mm	736	fuel cap	lt	71	
ground cl.	mm	130	Dry weight	kg	177	G.L.

Figure 8. Maxi scooter prototype on driving test (50th percentile male).

The software allows for the analysis of any combination of driving test paths (trajectory, time history, engine power, etc.), motorcycle prototypes, and body sets.

Note that it is possible to analyse different populations using the same simulations just by changing mean value and standard deviation of height. In fact, the four body sets (5th, 50th female and

50th, 95th male percentiles) can be used for different populations, representing different percentiles. The weights calculated according to (6) will differ depending on the population and the chosen mix coefficient.

A four-pins-ten-meter-step slalom was chosen as a driving test path. A calibration was made preliminarily for the dynamic behaviour of the rider-motorcycle coupling. For example, the force on the handlebar was measured preliminary on a test rig with a real motorcycle.

Table **4** shows the summary results for the chosen motorcycle prototype and driving test path. $L_{\text{dynamic},i}$ is the sum of losses calculated for all joint angles. Energy factors are calculated for each body set.

Table 4. Overall results for the maxi-scooter prototype.

Body set	**50th male**	**95th male**	**5th female**	**50th female**
w_i	0.45	0.18	0.02	0.34
$L_{\text{dynamic},i}$	2.78	4.96	61.68	24.44
$E_{f,i}$	0.23	0.25	0.46	0.43
$w_i * L_{\text{dynamic},i} * E_{f,i}$	0.29	0.22	0.57	3.57
Partial $E\left\{L_{tot,generalized}\right\}$ *by gender*	0.51		4.14	

Based on equation (13), we find $E\left\{L_{tot,generalized}\right\} = 4.65$. This score is quite low since the posture imposed by the maxi-scooter is very close to a neutral one. The study found that a touring-type motorcycle has an $E\left\{L_{tot,generalized}\right\} \approx 9.00$, while that for a racetrack motorcycle is around 15.

By examining the dynamic loss and the energy factor for only one body set (see Table 5), a racetrack-type motorcycle was found to have an energy factor lower than a touring-type motorcycle. This is due to the particular position of high body barycentre, limited movement of masses, and limited steering component. Naturally, the dynamic comfort loss is higher. However, a racetrack motorcycle rider prefers an energy factor more than dynamic comfort loss.

Moreover, comparing the ratios of average speed on the test path to energy factor (last row in Table 5) – which is a performance index – shows that the maxi-scooter and the racetrack are almost equivalent. Note that for the particular choice of motorcycle models, the average speed on the test path for the touring type is higher than the racetrack type.

Table 5. Comparison of performances of three motorcycle types (body set 50th male).

Motorcycle type	Maxi-scooter	Touring	Racetrack
Dynamic loss	2.78	26.31	45.60
Energy factor	0.23	0.36	0.32
Generalised loss	0.639	9.472	14.592
Average speed on the test path (m/s)	8.87	12.38	12.33
Average speed on the test path / energy factor	38.57	34.39	38.53

5. Conclusion

This paper provides a methodology for evaluating the comfort feeling on motorcycles, not just by considering a static posture, but also by considering dynamic behaviour, the masses, the loads, and performances on a simulated driving test. This work was developed from the Robust Ergonomic Design perspective, and evaluated the ergonomic impact of a motorcycle design on a reference population of riders. The purposely developed software allows changing of the reference population, while keeping the same human body sets and recalculating their relative weight for the population under study. This aspect is very important for saving time during concept development phases.

The methodology can be used in design phases when some information is known about both the target rider population and the features of the motorcycle. Expected driving strategy is also important, as it influences overall comfort.

The considerations presented in this article allow a generalised ergo-dynamic evaluation rather than simply an ergonomic one.

The proposed evaluations are based on computer simulations. However, further developments could be made with the support of physical experiments, since it has been demonstrated (see e.g. Fritzsche, 2010) that through physical experiments it is possible to catch some microergonomic aspects which are very hard to analyse in simulation studies.

References

Andersson P. (1997). On Robust Design in the Conceptual Design Phase: A Qualitative Approach. Journal of Engineering Design, 8(1), 75–89.

Barone S. and Curcio (2004). A computer-aided design-based system for posture analyses of motorcycles. Journal of Engineering Design, 15(6).

Barone S. and Lanzotti A. (2002). Quality engineering approach to improve comfort of a new vehicle in virtual environment. Proceedings of the American Statistical Association.

Barone S. and Lanzotti A. (2007). On the treatment of anthropometrical noise factors in Robust Ergonomic Design. In Proceedings of Congreso Internacional Conjunto XVI ADM – XIX INGEGRAF, Perugia (Italy) 6-8 June 2007. ISBN 978-884671841-9.

Barone S., and Lanzotti A. (2009). Robust Ergonomic Virtual Design. In: Statistics for Innovation - Statistical Design of continuous product innovation. Ed. P. Erto. Springer. ISBN: 978-88-470-0814-4.

Barone S., Lo Iacono G. and Pampinella S. (2010). Progettazione emozionale statistica: esempio di applicazione a moto di media cilindrata. ATA – Ingegneria dell'Autoveicolo, 63(7/8).

Barone, Lombardo and Tarantino (2007). A Weighted Logistic Regression for Conjoint Analysis and Kansei Engineering. Quality And Reliability Engineering International, 10.1002/qre.866.

Bubb, H., Estermann, S. (2000). Influence of forces on comfort feeling in vehicles. SAE technical paper series 2000-01-2171.

Chang, S., Wang M.J, (2007). Digital Human Modeling and Workplace Evaluation Using an Automobile Assembly Task as an Example. Human Factors and Ergonomics in Manufacturing, 17 (5), 445–455.

Chou, J.R., Hsiao, S.W. (2005). An anthropometric measurement for developing an electric scooter. International Journal of Industrial Ergonomics, 35, 1047–1063.

Chung, S.J, Park, M.Y. (2004). Three-Dimensional Analysis of a Driver-Passenger Vehicle Interface. Human Factors and Ergonomics in Manufacturing, 14 (3), 269–284.

Collins M., Brown B., Bowman K. and Carkeet A. (1990). Workstation variables and visual discomfort associated with VDTs. Applied Ergonomics, 21(2), 157–161.

Fritzsche L. (2010). Ergonomics Risk Assessment with Digital Human Models in Car Assembly: Simulation versus Real Life. Human Factors and Ergonomics in Manufacturing, 20 (4), 287–299.

Gilad I. and Karni R. (1997). Architecture of an expert system for ergonomics analysis and design. International Journal of Industrial Ergonomics, 23, 205–221.

Greil H. (1988). Body dimensions of adults, a representative anthropological cross-sectional study in Germany, PhD thesis, Humboldt University, Berlin.

Hasenkamp T., Arvidsson M., Gremyr I. (2009). A review of practices for robust design methodology. Journal of Engineering Design, 20(6), 645–657.

Motta R. and Bordone M. (2003). Biomechanics of tendons in physiological and pathological conditions (in Italian), unpublished bachelor thesis, University of Pavia, Italy.

Nagamachi, M. (1989). Kansei Engineering. Kaibundo, Tokyo.

Noy, I. (Ed.). (1997). Ergonomics and safety of intelligent driver interfaces (human factors in Transportation). CRC Press.

Park S.J., Kim J.S., Kim C.B. (2010). Comfort Evaluation and Bed Adjustment According to Sleeping Positions. Human Factors and Ergonomics in Manufacturing, 19 (2), 145–157.

Porter M. and Gyi D.E. (1998). Exploring the optimum posture for driver comfort. International Journal of Vehicle Design, 19(3), 255–266.

Reed M. and Flannagan C. (2000). Anthropometric and Postural Variability: limitations of the Boundary Manikin Approach. SAE Technical Paper Series 2000-01-2172.

Robertson S.A. and Minter A. (1996). A study of some anthropometric characteristics of motorcycle riders. Applied Ergonomics, 27, 223–229.

Vogt C., Mergl C. and Bubb H. (2005). Interior layout design of passenger vehicles with RAMSIS. Human Factors and Ergonomics in Manufacturing, 15(2),197–212.

Wilson J.R. (2000). Fundamentals of ergonomics in theory and practice. Applied Ergonomics, 31, 557–567.

Chapter 5

Creation of a VBA software for motorcycle digital mock-up, comfort-dynamic assessment

Industrial Engineering Dept (DICGIM - UNIPA)
UNIVERSITÀ DEGLI STUDI DI PALERMO

Creation of a VBA software for motorcycle digital mock-up, comfort-dynamic assessment

Giovanni Lo Iacono

Abstract

In the design process a matching between man and machine has to be done at several different levels. Here the aim is to examine at least two aspects: the physical matching and the cognitive process the user establishes with the machine.

The object of our investigation is the motorcycle, made by shapes and features, while the rider is the subject: he represents both an anthropometric model to be designed and the decision making centre as user. In the design process both human model and machine design have to be considered firstly under an ergonomic perspective. Then the engineer has to consider both the driving strategy and the dynamic response of the vehicle under a cognitive perspective answering to the question: how position and consistency of commands affect driving strategy and dynamic behaviour? The two flows, both ergonomic and cognitive, affect the subjective idea of comfort in user. So anthropometrical and psychological variations among different users, affecting both the processes, are noise factors for comfort feeling. The two flows have to be considered in both directions because a one way ergonomic flow from man to machine obstacles the evolution of by always design imposing primitive constraints. Vice-versa a reverse one way flow from design to man creates futile design, without a real possibility to use the machine. Looking at the cognitive flow we can think it as a transmission of controls from the user to the machine and feedback signals from the machine logic to user perception. A one way flow from user to machine logic could the one of a system where user training need and sustainability principles are no longer required within machine design: it is dangerous because it limits the components life and doesn't respect the environment. Vice-versa a very advanced machine logic is useless if the average user is not able to use it. Both flows have to be taken into account in both directions while the design process has to work in the middle between man and machine. A loop between these four pivots (anthropometric model, user logic, machine design, machine logic) generates the ergo-dynamic process, involving both hardware and software, both physical design and cognitive aspects of man-machine interaction, which is not only a shape models matching (ergonomic flow) but also a rational matching between user and machine logic (cognitive flow). In this work a new design methodology is further developed by writing a specified dedicated software which uses an homocentric perspective introducing, beside the traditional physical design, the dynamics of the human-machine interaction, and the driving style strategies.

Keywords: human-machine interface, ergonomics, driving logic controls, digital mock-up, motorcycle dynamics simulation

Introduction

The importance of the ergonomic component inside the motorcycle general design is due to the mock up realization costs, and to the importance of the physical component both in ergonomic and in performance aspects. It's interesting to look at the difference with the automotive sector, where the ergonomic factor already represents a fundamental issue: the massive ratio between driver and machine is definitively higher, from 0,25 to 2, while in the automotive sector it is always lower than 0,1.

In motorcycle driving, comfort feeling is a pre-requisite for safety and customers should be able to evaluate a comfort numeric indicator in the same way as they can do with the engine power or other quantitative features. Comfort feeling steps from the simple static matching between human body and machine, and the anthropometrical variation is one of the main noise factors to take into account for human model drawing.

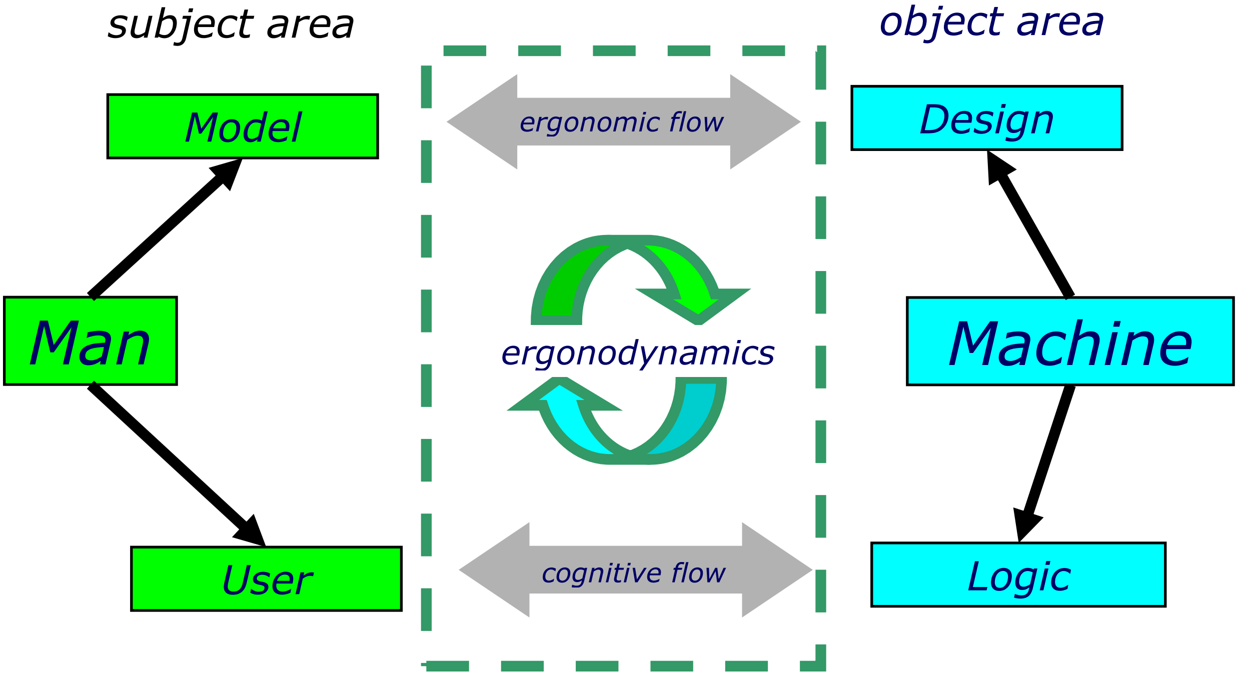


Figure 1. Man – Machine interaction

The underlying methodology of the tool which is going to be introduced steps from the knowledge of the impact of anthropometric variation over a reference population in product placement.In the meanwhile it gives a feedback over the dynamic performance in terms of energy effort level required to the rider, and general performance of the motorcycle.This circumstance allows competitiveness since the early design phases because unable makes possible a single designerto make evaluations about vehicle geometries, weight distribution, static ergonomics, suspension loads, motorcycle performance, dynamic ergonomic.

Using this Visual Basic tool, based on Robust Design techniques, allows a considerable cost reduction within the prototyping phase, by analyzing the main designs with very quick computer experiment analysis, eliciting to build a few prototypes addressed by the global virtual evaluation. The tool simulates the entire motorcycle building, through a tri dimensional localization of all the heavy components within a local reference, with a bi-dimensional graphic representation of all the views needed to sizes understanding.

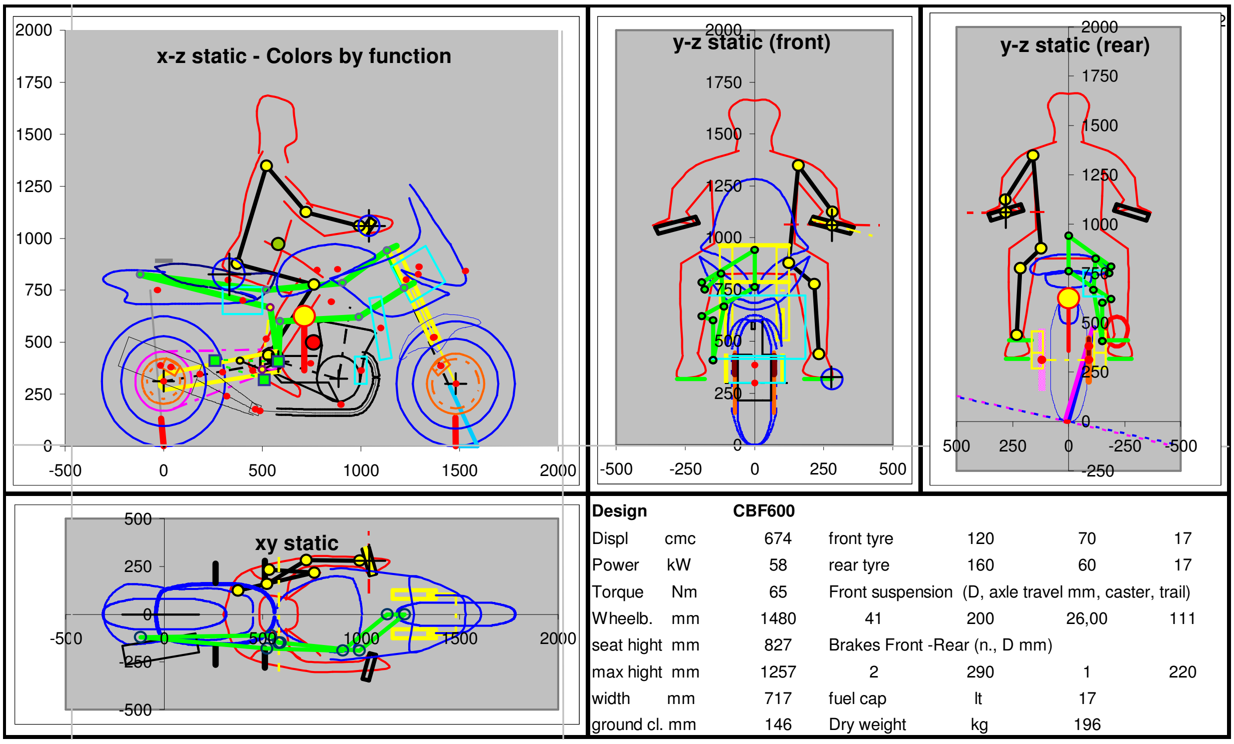
All the main aesthetic components (tank, fairings, lights, mudguard, seat) are represented by Bezier curves, coherent among different views. The engine drawing is an assembly of modular solids proportional in dimensions to the referring item (carter, cylinders, heads), coherently to specifications as gears, stroke, bore. The motorcycle is analyzed with by imposing a three-dimensional motion state, where time depends on engine and motorcycle dynamic features. The imposed path is an assembly of parametric curves. The static postures of rider and pillion come from a static matching with the motorcycle constraints (seat, footboards, steer etc.), according to well known ergonomic standards, while the dynamic comfort evaluation depends on the interface loads coming from dynamic performance of the rider-motorcycle binomial, or the rider-motorcycle-pillion trinomial.

Understanding motorcycle dynamics allows to identify in a quantitative way the loads stressing all motorcycle components during a specified usage, providing several inputs for the optimization procedures within a radical design, but prototypes building for experimental measurements would be extremely expensive, while prototyping variation could affect experimental reproducibility. Other issue is the repeatability the performance is affected by, during a wired machine testing, despite the tester skills: he can't guarantee ever the same a manoeuvre. A computer experiment "filter", concerning both the ergonomic and dynamic aspects, is so required in order to reduce the experimental sessions.

Moreover the tester subjective judgements are no scientific statements, since they involve specific driving styles and personal skills, both technical and communicative. These fundamental professional strengths would be better utilized during a fine tuning session with few good prototypes, while a computer experiment feeling evaluation could help avoiding bad prototypes money wasting. Yes, the "feeling" concept is hardly measurable within a simulation, but some recent studies show a significant effort in this direction (Barone & Lo Iacono, 2011).The present ergo-dynamic simulation can provide a general objective overview of product-user binomial behaviour, enabling many output parameters reading.

1. Tool description

This tool, firstly created with an excel file format, including a wide set of Visual Basic Macro, requiring solver.xla on dll library, is built using the bi-dimesional CAD logic, where all the components are drawn inside several independent files with local references, imported in an assembly file, pointing to the components, and positioning them in a general global reference system. In this case several worksheets define point by point some three bi-dimensional views of all the components, while a worksheet "ASM" points to the arrays describing these items and making a reference change.



Design		CBF600				
Displ	cmc	674	front tyre	120	70	17
Power	kW	58	rear tyre	160	60	17
Torque	Nm	65	Front suspension (D, axle travel mm, caster, trail)			
Wheelb.	mm	1480	41	200	26,00	111
seat hight	mm	827	Brakes Front -Rear (n., D mm)			
max hight	mm	1257	2	290	1	220
width	mm	717	fuel cap	lt	17	
ground cl.	mm	146	Dry weight	kg	196	

Figure 2. Motorcycle synthesis window

This tool simulates the motorcycle assembly in all the main components, by localizing the heavy ones on a general reference. The most of aesthetic important items (tank, fairings, lights and seat) are represented by Bezier parametric curves, coherent across the different views. The engine is represented with regular geometric shapes, coherently with its specifications. Global reference has origin on the ideal contact point between the rear wheel and the road, where power transmission takes place. The plane XZ is the sagittal plane, containing the longitudinal wheelbase dimension, represented by X variable and the high, as distance from ground, represented by Z variable. The width, represented by Y variable, determines with Z the YZ front/rear plane.

Main geometric dimensions

- e Steering angle
- d Steering offset
- P wheel base
- ε Caster angle
- R_f Front wheel radius
- R_r Rear wheel radius
- t_f Front tire section radius
- t_r Rear tire section radius

Other important geometrical dimensions depend on the previous:

$\rho_f = R_f - t_f$, Front wheel torus axis radius

$\rho_r = R_r - t_r$, Rear wheel torus axis radius

$a_n = R_f \text{ sen } \varepsilon - d$,Mechanical trail

$a = a_n / \cos \varepsilon = R_f \text{ tg } \varepsilon - d/\cos \varepsilon$, Trail

2. Digital mock-up building

The main dimensions are introduced inside the worksheet “ASM”, where they are used to create the functional items depending on them, like wheels, suspensions, frame, transmissions, etc.. In “ASM” there are also the arrays pointing to other worksheets, representing the main aesthetic components. These elements, mainly defined by Bezier curves, are modulated with a visual approach, by tuning the control polygon, representing a split curve the Bezier curve is attracted from, with different boundary conditions, as well as they are external or median parts, then with tangent condition or variable attraction, depending on the multiplicity of the control points. The following graph represents the fairing plot XZ , in a local reference, where is possible to appreciate the way the control polygon (grey split curve) works moving the generated profile (red curve).

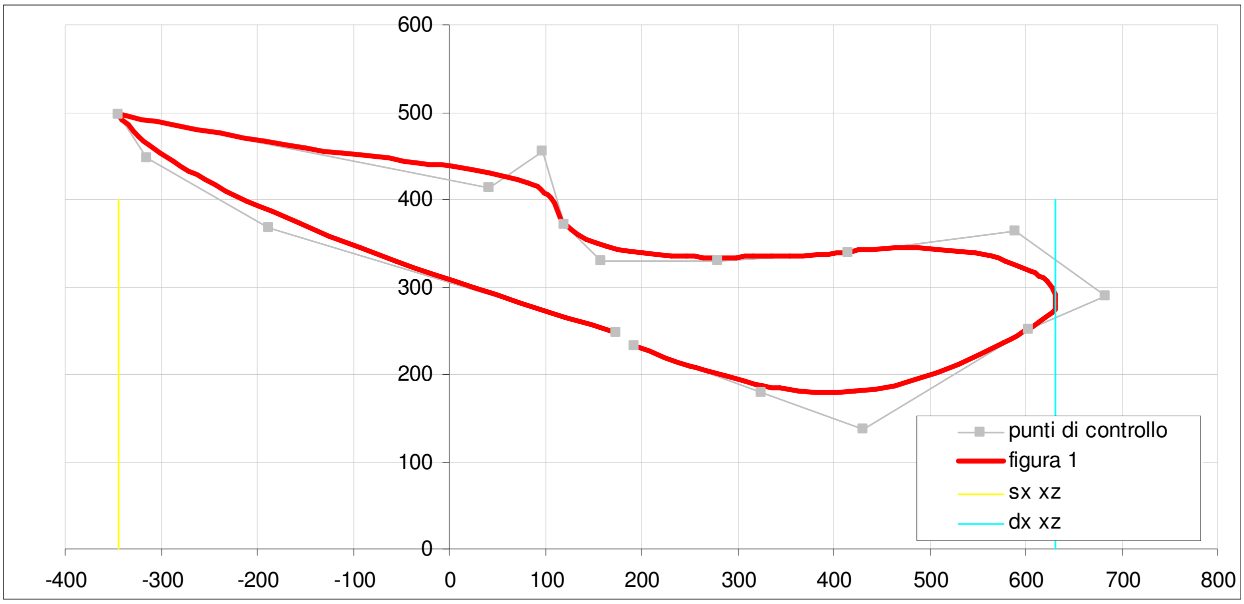


Figure 3. Seat profile construction through split curve controlled parametric curve

The cyan and yellow lines limit the seat lateral size: they are useful to fix the general dimensions to be respected in a non contextualized drawing separated from the general assembly, and so not very intuitive concerning the proportions. The data are introduced in a table format inside the “ASM” worksheet, in the red label cells, while the black label cells contain the depending output variables. There are blocks of input and blocks of output, in order to visualize step by step the depending variables connected to the different interest areas.

There are in total 257 input and 420 output, excluding the values of the parametric curves control points coordinates, often localized inside the specified worksheets, but controllable also from “ASM” by the visual interactive approach, allowed by EXCEL® within the graphs. ®The following table shows a compilation example, with the first lines of the “ASM” worksheet, concerning the digital mock-up of a Honda CBF 600 S.

Data regarding mass properties, needed for the cinematic and dynamic analysis, can be introduced as input or automatically calculated using the available information, as geometries and material density. The calculation has been validated by matching the results with existing items, whom principal physical characteristics were known, as mass and inertia moments.

Table 1. Motorcycle main input-output synthesis table

	Geometria generale	*CBF600*	output	
Wheelbase	**int_asse**	1480,00	1480,00	[mm]
Caster	**caster**	26,00	26,00	[deg]
Front end offset	**offset_canotto**	32,00		[mm]
Front tyre width	**largh_pneu_f**	120,00		[mm]
% radial torus front tyre	**spall_pneu_f**	70,00		[-]
Front pitch circle	**d_cerchio_f**	17,00		[inch]
Rear tyre width	**largh_pneu_r**	160,00		[mm]
% radial torus rear tyre	**spall_pneu_r**	60,00		[-]
Rear pitch circle	**d_cerchio_r**	17,00		[inch]
Top caster front axis vertical distance	**Dh_vert_sup-ax_ant**	640,10		[mm]
Swing arm abscissa	**x_AX_forcellone**	468,00		[mm]
Swing arm distance from ground	**z_AX_forcellone**	406,00		[mm]
Top caster distance from ground	**h_vert_sup**		940,00	[mm]
Normal trial	**a_n**		99,47	[mm]
Trial	**a**		110,67	[mm]
Front wheel radius	**Rc_f**		215,90	[mm]
Rear wheel radius	**Rc_r**		215,90	[mm]
Front tyre external radius	**R_f**		299,90	[mm]
Rear tyre external radius	**R_r**		311,90	[mm]
Total length	**L_tot**		2091,80	[mm]
Motorcycle mass	**m_moto**		184,09	[kg]
Driver mass	**m_driv**		72,04	[kg]
Pillion mass	**m_pill**			[kg]
Total load mass	**m_mann**		72,04	[kg]
Extra loas mass	**m_carico**	0,00		[kg]
Total simulation mass	**m_tot**		256,14	[kg]

3. Ergonomics

Anthropometric variability data are shown in the table below: they concern several stochastic variables as total height, shoulders height, groin position, etc. From these data a series of six manikins were drawn, whose body segments are coherent with. The six classes correspond to , 5°, 50° e 95 percentiles for both males and females.

Table 2. European Population Anthropometric characters

Antopometrical carachters [cm]	MAN percentiles 0,05	 0,50	 0,95	WOMAN percentiles 0,05	 0,50	 0,95
set	1	2	3	4	5	6
height	1620,00	1733,00	1841,00	1510,00	1610,00	1725,00
shoulders	1340,00	1445,00	1542,00	1230,00	1339,00	1436,00
groin (cavallo)	752,00	816,00	886,00	670,00	720,00	770,00
orizzontal action radious (operating hand axis)	662,00	722,00	787,00	616,00	690,00	762,00
eyes level height	1500,00	1613,00	1721,00	1402,00	1502,00	1596,00
vertical action radious (operating hand axis)	1910,00	2051,00	2210,00	1748,00	1870,00	2000,00
pelvis width (up standing)	310,00	344,00	368,00	314,00	358,00	405,00
hand axis height	728,00	767,00	828,00	664,00	738,00	803,00

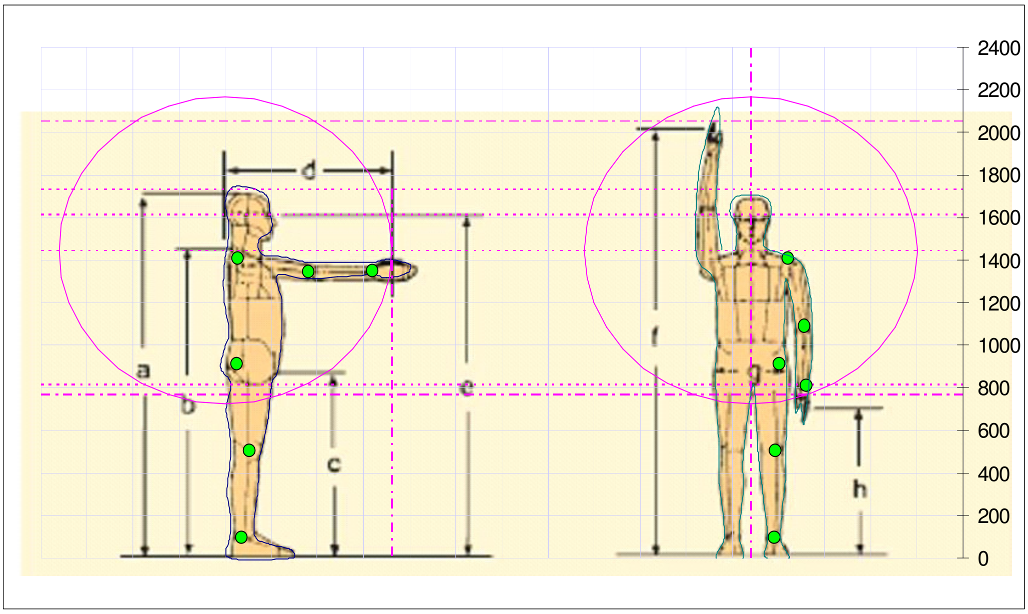


Figure 4. Anthropometric modelling

These manikins match with the motorcycle design, by copying its geometrical constraints. This matching generates the orientation of the body segments and so the articulation angles contributing to the comfort feeling generation.

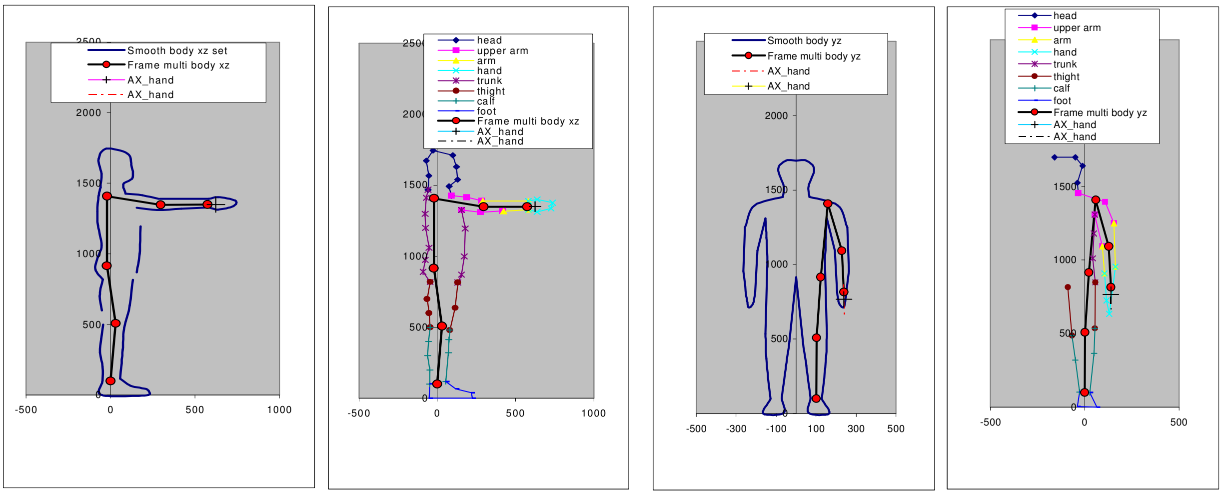


Figure 5. Anthropometric model building

The skeleton is modelled like a three-dimensional joints frame: each segment has one or two degrees of freedom with respect to the contiguous, depending on the constraints, collecting 14 DOF in total. This rider-machine matching is activated with the command FIT2(fit2), pointing to the corresponding macro. FIT2 is located in the worksheets both ASM and driver.

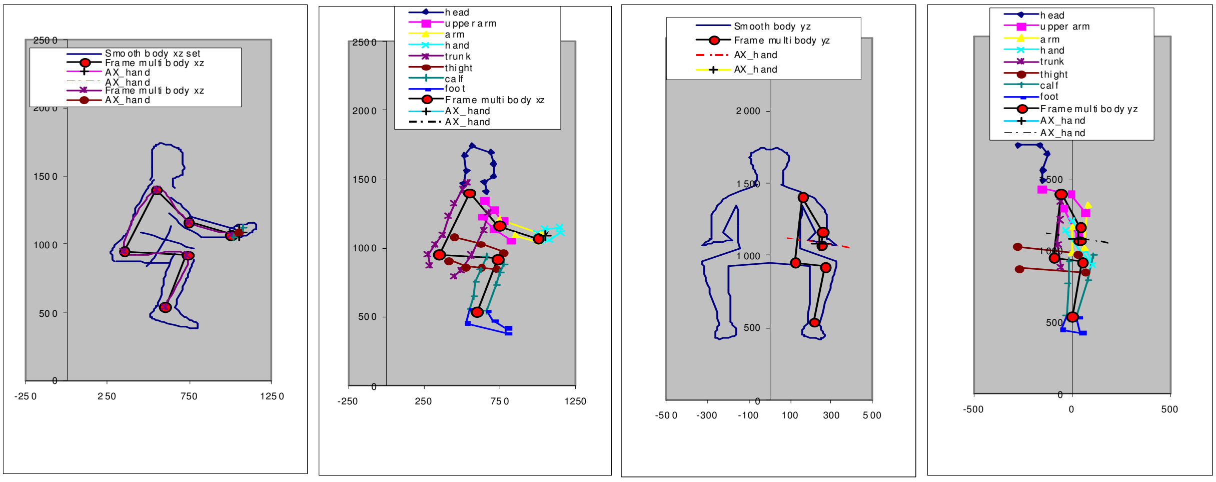
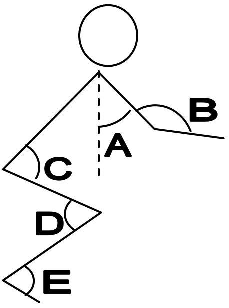


Figure 6. Animating the anthropometric mode

Comfort evaluation concerning the posture is done by following a method stepping from a paper published by Porter & Gyi, who in 1998 investigated the preferred posture by interviewing a car drivers sample, using a posture simulacrum which was leaving the possibility to vary the position of the body segments. Resulting data are collected on table 3.

Table 3. Minimum, preferred and maximum value of joint angles
(adapted from: Porter and Gyi, 1998)

Joint angle Y_j	**min** $y_{j,\min}$	**preferred** τ_j	**max** $y_{j,\max}$
A Upper arm flexion	19	50	75
B Elbow angle	86	128	164
C Trunk-thigh angle	90	101	115
D Knee angle	99	121	136
E Foot-calf angle	80	93	113



Starting from these data, Barone & Lanzotti purposed, for each articulation, the joint angle between a couple of body segments, an asymmetric loss function, linear or quadratic, by imposing 100% of comfort loss at extremes of joint angles distribution, which is not symmetric respect the preferred joint angle. Obviously the loss function has a value of 0% in this preferred angle. The quadratic loss function is defined by:

$$L_j = L\left[Y_j(H)\right] = \begin{cases} \alpha_j\left[Y_j(H)-\tau_j\right]^2 & \text{if} \quad Y_j(H) \le \tau_j \\ \beta_j\left[Y_j(H)-\tau_j\right]^2 & \text{if} \quad Y_j(H) > \tau_j \end{cases} \qquad j = 1,\ldots,J \qquad (1)$$

where:

L_j is the comfort loss for the j-th joint angle;

Y_j is the joint angle value. It is a random variable due to the variation of body height H;

τ_j is the preferred value for each joint angle, according to Porter and Gyi (1998).

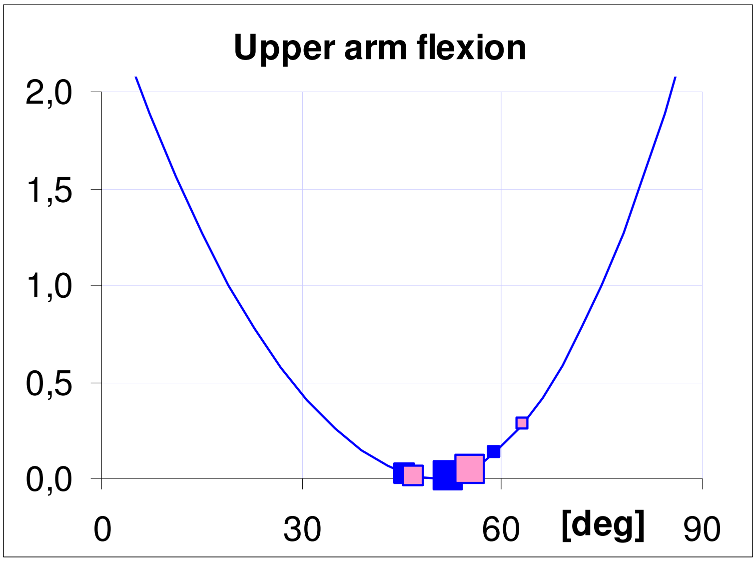
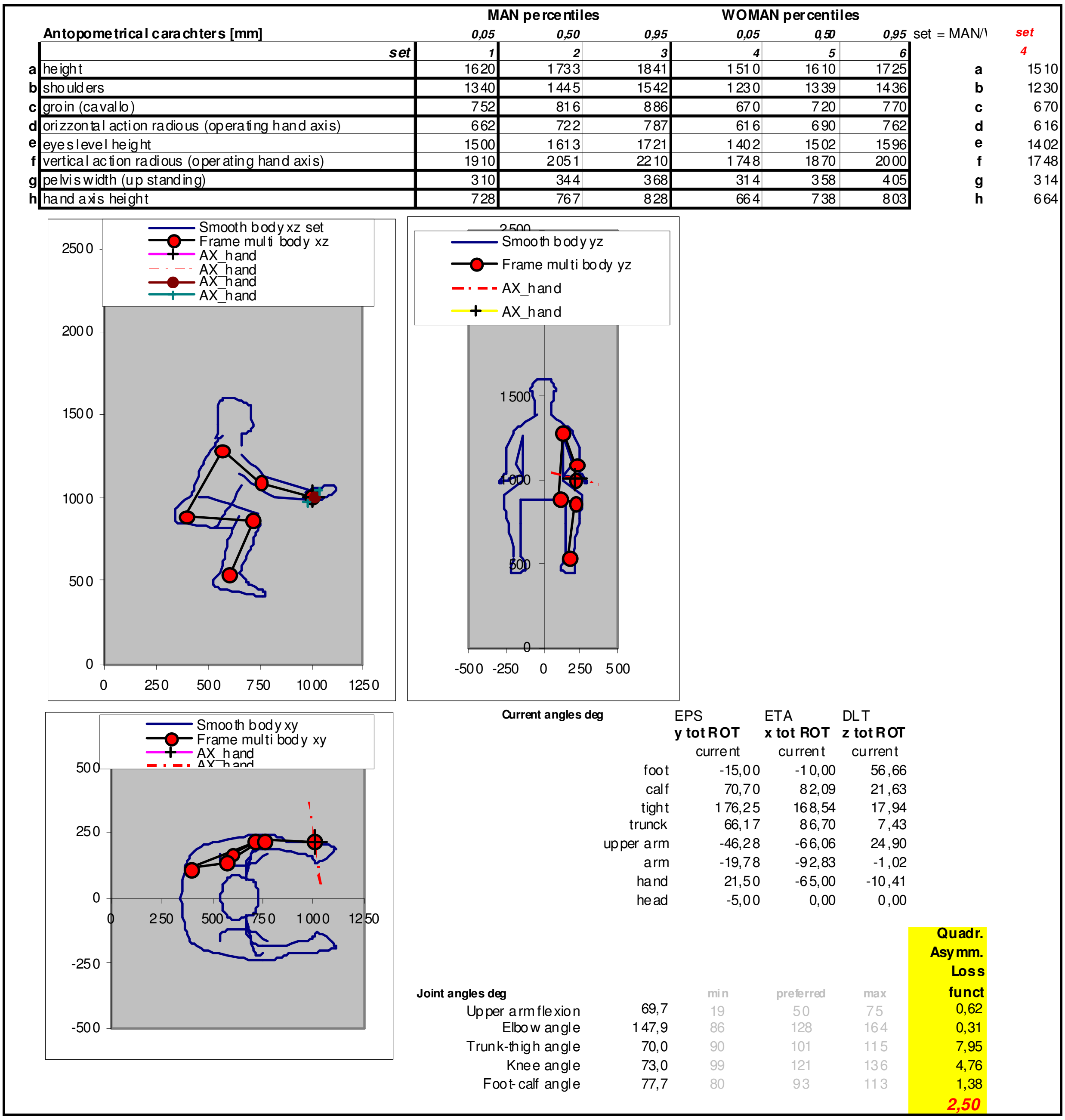


Figure 7. Comfort loss function

Inside the worksheet DRIVER is possible having an overview of the final posture (see figure 7) together with the comfort loss functions, summed according to a percentile weights criterion, giving values around 1/6 to percentiles 5th and 95th, and the rest 4/6 to the percentile 50th.



	Antopometrical carachters [mm]	**MAN percentiles**			**WOMAN percentiles**				
		0,05	*0,50*	*0,95*	*0,05*	*0,50*	*0,95*	set = MAN/\	*set*
	set	*1*	*2*	*3*	*4*	*5*	*6*		*4*
a	height	1620	1733	1841	1510	1610	1725	**a**	1510
b	shoulders	1340	1445	1542	1230	1339	1436	**b**	1230
c	groin (cavallo)	752	816	886	670	720	770	**c**	670
d	orizzontal action radious (operating hand axis)	662	722	787	616	690	762	**d**	616
e	eyes level height	1500	1613	1721	1402	1502	1596	**e**	1402
f	vertical action radious (operating hand axis)	1910	2051	2210	1748	1870	2000	**f**	1748
g	pelvis width (up standing)	310	344	368	314	358	405	**g**	314
h	hand axis height	728	767	828	664	738	803	**h**	664

Current angles deg	EPS **y tot ROT** current	ETA **x tot ROT** current	DLT **z tot ROT** current
foot	-15,00	-10,00	56,66
calf	70,70	82,09	21,63
tight	176,25	168,54	17,94
trunck	66,17	86,70	7,43
upper arm	-46,28	-66,06	24,90
arm	-19,78	-92,83	-1,02
hand	21,50	-65,00	-10,41
head	-5,00	0,00	0,00

Joint angles deg		min	preferred	max	**Quadr. Asymm. Loss funct**
Upper arm flexion	69,7	19	50	75	0,62
Elbow angle	147,9	86	128	164	0,31
Trunk-thigh angle	70,0	90	101	115	7,95
Knee angle	73,0	99	121	136	4,76
Foot-calf angle	77,7	80	93	113	1,38
					2,50

Figure 8. Driver Posture synthesis window

Beside the static ergonomic vision, a dynamic one is possible through the articular momentum computation: they come out posture by posture, integrating in a non dimensional way the comfort indexes given by the above shown loss function.

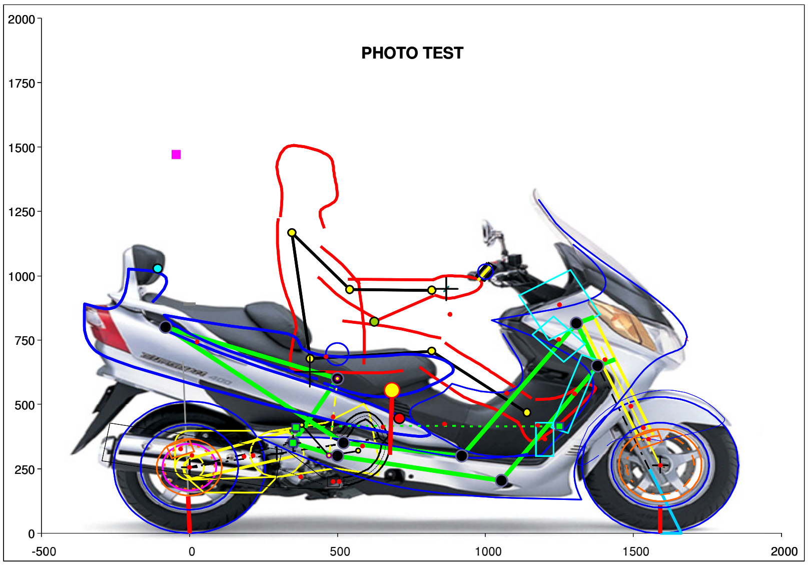
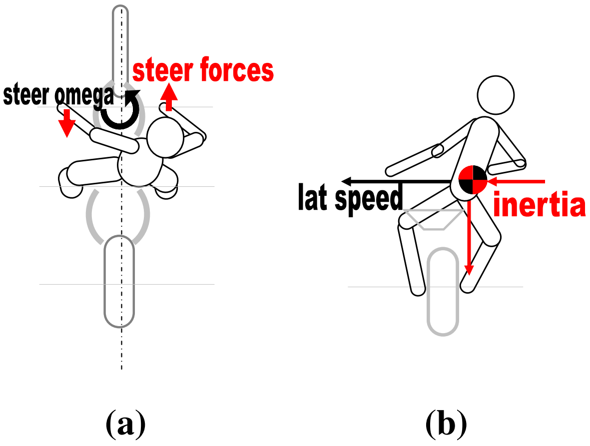


Figure 9. Existing design digital mock-up checking

Introducing then the torsions beside the moments, and the motions beside the forces, an evaluation of the energetic effort the driver has to afford on a standard path is achieved. Neglecting friction and the pressure between rider body and motorcycle seat and tank, we assume that the rider spends energy in two possible ways: for the steering rotation (*a*) (see figure 10a); for shifting his/her barycentre to obtain the rolling equilibrium (*b*) (see figure 10b). This energetic effort can be insert within the dynamic comfort evaluation, or utilized separately in order to compare different machine designs, while the requirements regard not the posture but just the driving energy. In both cases a logic vehicle control development is strongly required, since the cinematic-dynamic simulation has to start from the man-machine interface, and then extend to the motorcycle dynamics.



(a) **(b)**

Figure 10. Driver Energy efforts scheme

4. Defining the vehicle control logic

Driving experience and style are, from the manufacturer perspective, stochastic variables as well as anthropometric data: they change rider by rider and each rider experience changes, motorcycle by motorcycle: for example a racetrack motorcycle posture forces the driver to tight the arms as much as possible aligned to the forks, in order to get the right rolling force by moving the rider gravity centre, without generating a steering component, which leads instead to gyroscopic effects, a little destabilizing. On the other side the urban maxi-scooters (especially the Japanese ones) compel driver to feel free on lateral movements when turning, while the footboard is designed to guarantee a backward position of rider on the seat, because a steering component is strongly required since the little front wheel drives the vehicle mostly without heavy gyroscopic effects, being limited by inertias and speed, within so called manoeuvred stability. Big normal loads on front wheel are avoided, which would be a bad feature for a urban commuter affording every day the disconnections of the city asphalt.

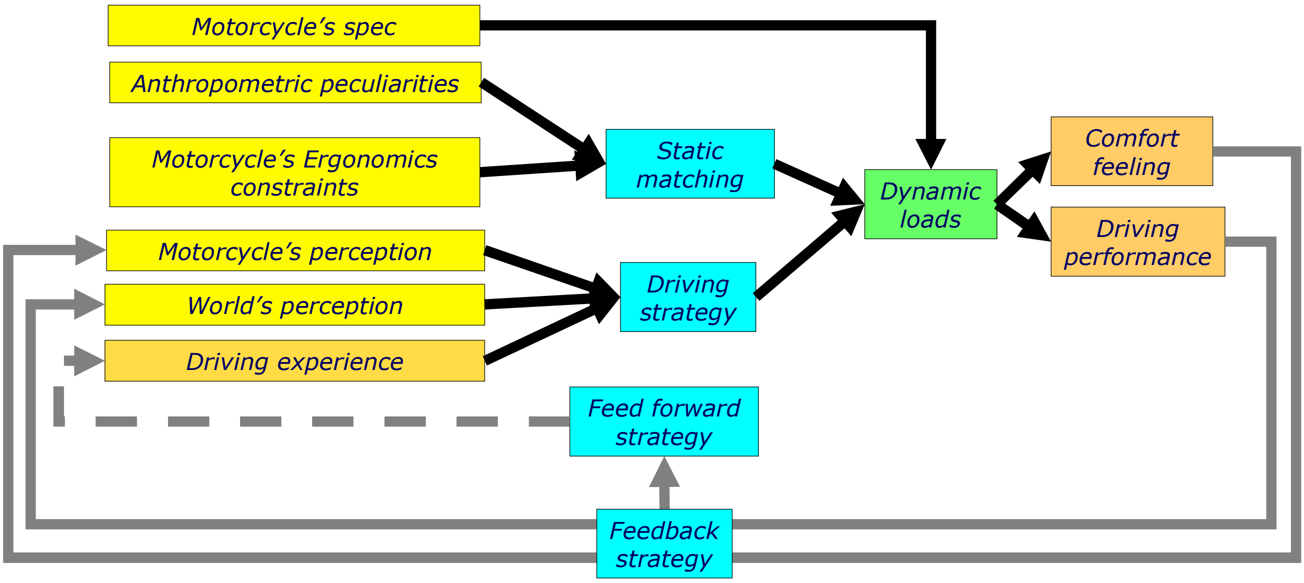


Figure 11. Driving experience and feed forward strategy

Moreover driving experience, or generally speaking human skills, change day by day because comfort feeling and driving performances vary all the brain procedures in time. Let's consider the natural position of astronauts: the first month in orbit they start retreating backwards the bottom in order to limit the absence of gravity related discomfort by keeping the mass centre on a stable equilibrium (Motta & Bordone, 2003). This strategy involves the feedback concept, as well as bottom retreating is the first solution they find using their instinct. After one hundred days in orbit, the final posture of the astronauts is observed to be more tilted forward than before the mission, which is the best solution to maximize the speed walking and stability: this strategy rather involves the feed-forward concept, as well as it doesn't stop at the first solution for the equilibrium, (local point of minimum, see figure 12), getting finally better results in walking. As a consequence improving a posture performance increases the comfort loss. So under an improve perspective, the comfort has not to be as much as possible, but coherent with machine and user target.

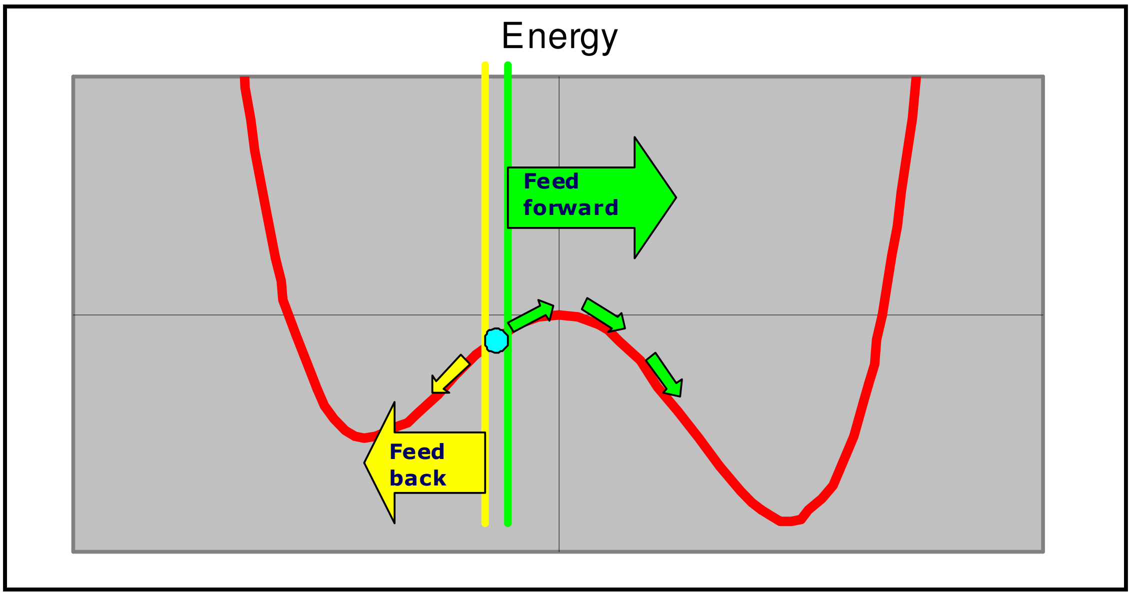


Figure 12. Feed back and feed forward strategies

These reflections have been driving this research in order to understand the logic of human brain on establishing priorities while affording the driving task.

So the aim of this work was to create a series of simple feedback controls, within a software language with a graphic interface, and compose them through a feed forward strategy. The out-coming logic is the nearest picture to the brain accommodation skills we could get.

5. Measuring and quantifying vehicle DOF and related control logics

The degrees of freedom of a motorcycle (see figure 13), and their direct main controls within curve trajectory are: a) lateral movement, controlled by power transmission (gas), b) jaw angle, controlled by steering angle (steering torque), c) roll angle, controlled by gravity centre position (rider offset).

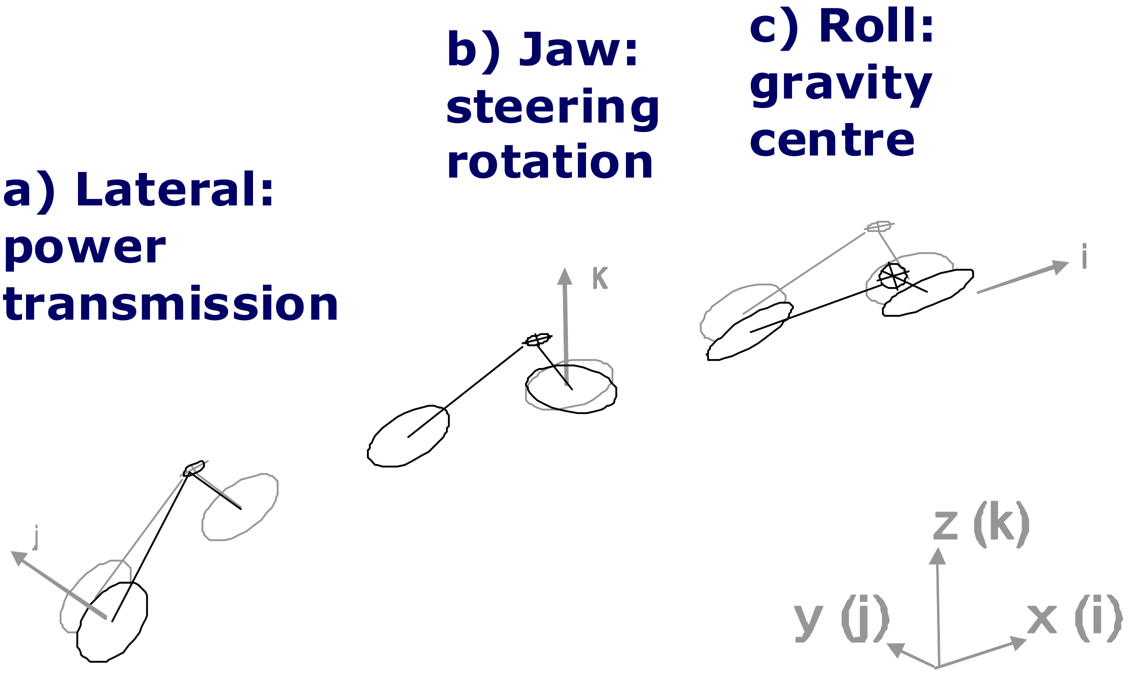


Figure 13. Cornering Motorcycle degrees of freedom and related control parameters

The governing equations are:

a) $$m \cdot \frac{v_x^{\,2}}{R_y} - N_z \cdot u_s = m \cdot a_y$$

b) $$C_{st} - \overrightarrow{N_{z,f}} \times \overrightarrow{a_n} = I_{st} \cdot \alpha_{st}$$

c) $$m \cdot \frac{v_x^{\,2}}{R_y} \cdot z_G - m \cdot g \cdot Y_G - m_{rid} \cdot g \cdot e_y = I_x \cdot \alpha_x$$

Where: XYZ is an inertial reference; m is the motorcycle-rider mass; v_x is the speed; R_y is the trajectory curvature radius ; N_z is the normal road reaction; u_s is the (static/dynamic) friction coefficient; a_y is the radial acceleration ; C_{st} is the rider steering torque; $N_{z,f}$ is the normal road reaction on front wheel; a_n is the normal trail; I_{st} is the steering inertia moment; α_{st} is the steering angular acceleration; z_G is the system gravity centre high on ground; m_{rid} is the rider mass; e_y is the rider mass eccentricity; I_x is the longitudinal system inertia moment; α_x is the longitudinal system angular acceleration.

The equation a) is general for both rear end and front end, so masses and normal reactions are specific and coming from pitch equilibrium, later explained. Within the b) equation the steering angular acceleration is calculated by adapting the steering rotation to the instantaneous trajectory curvature radius, including front and rear derives effect, following the scalar relation:

b') $\vartheta_n - (\lambda_f - \lambda_r) \cong P / R_y$;

where, non considering rolling effect: θ_n is the normal steering angle, depending on effective steering angle and caster angle; λ_f and λ_r are derive angles on front and rear wheels, due to sliding, and depending on friction and tires stiffness; P is the wheel base, which divided rates the curvature radius returns the desired curvature angle. The computation has also a trigonometric correction including the rolling angle. For an imposed trajectory the only one dependent variable is θ_n.

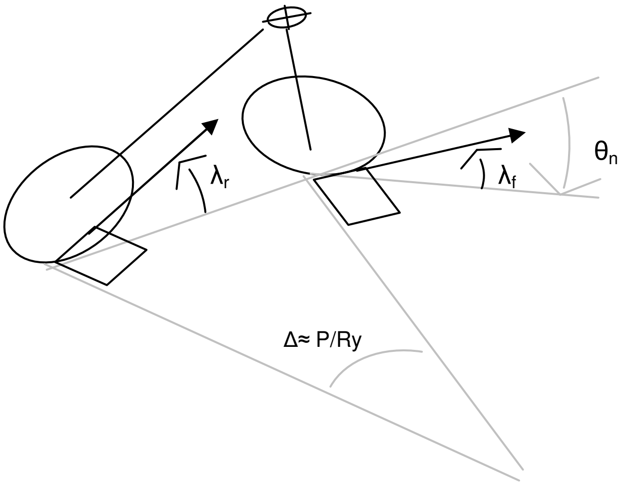


Figure 14. Normal steering angle calculation

Three macro control a) b) c) output by tuning the corresponding input within a feedback logic, well simulated by the Visual Basic objective research function where only one of the input is required to solve the system, while the other variables play as boundary conditions. Each of them has an activation button on figure 15, permitted by the easy interface of Visual Basic.

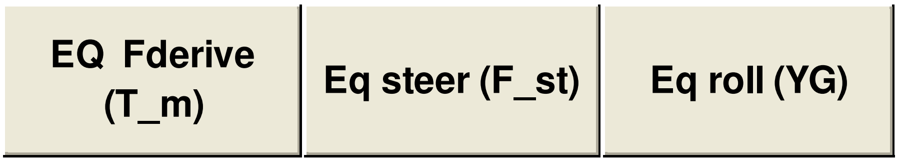


Figure 15. macro controlling basic driving skills (eq a, b, c)

- EQ_Fderive (T_m) tunes the throttle, or the percentage of engine torque, while maximizing it until physical limits as lateral or longitudinal derive, limited by contact grip;
- EQ_Fsteer imposes steering torsional equilibrium in caster axis, by tuning the arm forces the rider use to contrast the steering rotation coming out from the road reactions, combined with the specific geometry of the front suspension, including gyroscopic effects;
- EQ_roll (Yg) imposes a desired rolling acceleration by tuning the gravity centre position, or eccentricity, respect the sagittal plane;

The three controls are in rider capability, and a simultaneous use is required to get basic driving skills. An add basic skill concerns the brakes use, controlling the instantaneous speed, governed by:

d) $$F_{lev} \cdot \left(\frac{D_{ps}}{d_{pm}} \right)^2 \cdot u_d \cdot R_{dk} - m \cdot a_x \cdot R_w = I_{y,w_i} \cdot \frac{a_x}{R_{w_i}};$$

where: F_{lev} is the lever braking force; D_{ps} is the brake piston equivalent diameter; d_{pm} is the brake pump diameter; u_d is the disk-brake dynamic friction coefficient; R_{dk} is the brake disk medium radius; R_w is the braking wheel radius; $I_{y,w}$ is the wheel inertia rotation momentum; subscript i indicates where implicit sum for front and rear end is required; a_x is the desired bike acceleration, which is, only in braking phase, a target to get by tuning the lever force. Within this equation the friction force is supposed to be inside grip limit. Otherwise it is limited as in following equation e). Aerodynamic component is for simplicity hidden, but computation includes it as on following equation e).

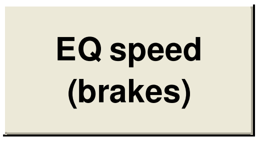


Figure 16. Macro controlling braking force (eq. d)

- EQ_speed_brakes control the speed by tuning braking force at rider level (pedal or lever force commands);

There are other motorcycle DOF like engine rotation speed, pitch angle, and suspensions compression, but they are not the in the rider direct capability, since they are rather a consequence of interactions at first feedback approach level: so, in the cognitive rider perspective, they could belong to a feed forward control upper level.

e) $\max\left[\frac{T_{eng}\cdot\tau_{fin}}{R_r};N_r\cdot u_s\right]-N\cdot u_v+X_{aer}\cdot=m\cdot a_x$

f) $N=N_f+N_r=m\cdot g-Z_{aer}$
$N_f\cdot P-N_r\cdot(p-x_G)+\max\left[T_{eng}\cdot\tau_{fin};N_r\cdot u_s\cdot R_r\right]+R_{aer}\cdot(z_{aer}-z_G)=0$

g) $m_s\cdot\ddot{s}-c\cdot\dot{s}-k\cdot s=F_s$

where: $T_{eng}\cdot\tau_{fin}$ is the engine torque reduced on wheel; N_r and N_r road rear and front normal reactions; u_v is the rolling friction coefficient; $(X,Z)_{aer}$ are the aerodynamic resistance components; x_G, is the global mass centre local coordinate; z_{aer} is the aerodynamic pressure centre distance from ground; m_s is the equivalent suspension mass; s is the suspension compression with its first and second derivates $\dot{s},\ddot{s}$; c is the suspension damping coefficient; k is the suspension stiffness; F_s is the suspension external force coming from the road reaction. In equation e) a_x is an output of the torque the rider is able to require to the engine according to equation a). Equation f) returns the load transfer between front and rear wheels while acceleration is non zero. Equation g) is general for both suspension, where the specific geometry affects the way the road reaction gets the final component F_s.

Figure 17. Macro controlling motorcycle response to non driver inputs

The correspondent controlling macro are:

- EQ_engine speed tunes the engine revolution speed in order to get coherence with the vehicle acceleration resulting from the general equilibrium, for fixed torque level;
- EQ_Pitch imposes normal forces equilibrium in front and rear wheel by tuning the extra reaction on rear one during acceleration phase (load transfer);
- EQ_Suspens.dynamic returns the compression values of the suspensions by resolving the dynamics involving instant reaction loads, inertias, damping, preloaded springs reaction;

All these macro have been fine tuned and they are useful to generate the equilibrium of the single logic subassemblies, by changing one input factor at time: they are mechanical system solvers for each frozen instant. All the output related to these solvers are more or less independent from other system input since there isn't a strong interaction between the control parameters. So it is possible to assume the systems are "orthogonal". A time implementation was required to join together all the logic items of the machine, doing it over time. Under the over explained conditions a time implementation can be done after solving separately each system, and then freezing the dependent state variable output as input variable for next step (position, steer angle, roll angle, pitch angle, etc). The Eulero integration method, approximating the function derive with its incremental ratio connected to step *t-to*, was used as explained on eq. h) and the command is shown in figure 18:

h) $v_t \cong v_{t_0} + f'\cdot(t - t_0)$

where v_t is the generic dependent variable at time t, t_0 is the time step start, and f' is the derivate of function v (t) in t_0;

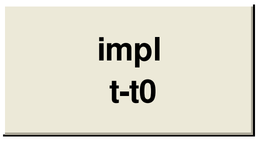


Figure 18. Macro activating Eulero implementation step

- Impl t-to implements the system through a fixed time step (t-t0), by freezing the output dependent variables at t0 as input boundary conditions at following time t;

Selecting "modo analisi 1" on cell C32, is possible to automatically insert the input trajectory data from three-dimensional arrays describing parametric space curves contained in the worksheets "dir-spi", "dir-bez" and "dir-bez2", respectively indicating the value 1, 2 or 3 in the cell H76. The analysis of the motorcycle degrees of freedom allow to understand the main feature of this machine is the capability of rolling round the baseline axis. And it increases the cornering speed by giving the possibility of equilibrating the rolling moments. Rolling triggering is so possible by controlling these moments: first in a direct way by moving the rider mass centre, second, in an indirect way, by generating gyroscopic effects described on i), j), k) equations, coming from angular moment derive (both on front and rear end):

$$\vec{L} = I \times \vec{\omega}$$

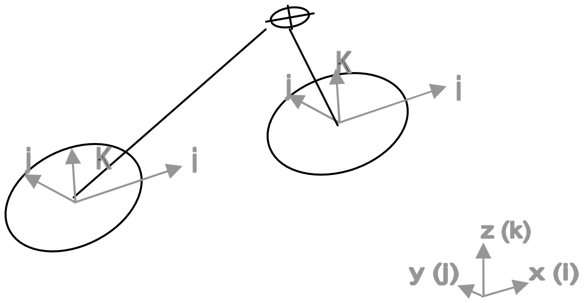
$$\vec{M} = \frac{d\vec{L}}{dt} \cong \vec{L} \times \vec{\omega} = \begin{vmatrix} \bar{i} & \bar{j} & \bar{k} \\ L_i & L_j & L_k \\ \omega_i & \omega_j & \omega_k \end{vmatrix}$$

Then gyroscopic components are:

i) $M_i = \omega_k \cdot I_j \omega_j - \omega_j \cdot I_k \omega_k$, rolling action

j) $M_j = \omega_i \cdot I_k \omega_k - \omega_k \cdot I_i \omega_i$, pitch action

k) $M_k = \omega_j \cdot I_i \omega_i - \omega_i \cdot I_j \omega_j$, jaw action



That's how they really work when the rider starts to afford cornering: firstly an interaction between front wheel angular speed and a sudden steering rotation generates the rolling action i) useful to start affording the curve: the equation highlights a clockwise curve requires an anticlockwise steering rotation; equation j) returns always zero being wheels axial symmetric, and accordingly $I_k = I_i$; then when a bigger enough rolling speed is reached a jaw action helps increasing cornering speed, according to equation k), by reducing curvature radius: this is possible through an increase of rear wheel sliding and a reduction of front wheel one (see equation b'); a secondary effect is a higher centrifugal force due to curvature radius reduction: theoretically a stabilizing effect, this feature requires the rider to induce a higher rolling angle, with the drawbacks of getting closer and close to the sideslip limits.

Due to secondary gyroscopic effects, combined with the particular geometry of the front suspension in motorcycles, the steering torque is idealistically capable of a wide control of trajectory, as well as destabilizing external effects, without a control of the rider weight eccentricity. With this assumption it could be possible building a toy with a motorcycle mechanic, and to drive it by using a remote control with only the steering motion. But the existing working models have the weight motion control. Indeed the force levels allowing this circumstance are not realistic, and above all, not consistent with the experimental data, which will shown later. Gyroscopic effects also are limited by effective speed: within a low one (around 30 km/h) they are negligible and the vehicle turns in the same direction as the steering. This phase is called manoeuvred stability, beyond whom gyroscopic effects affects more and more, but always in a non linear way and accordingly non predictable.

For this reason the weight eccentricity control has been taken as first control input, while the steering torque equilibrates only the correspondent signal coming from front wheel, also depending on the roll angle, which is a consequence of the first input tuning: there is a cause effect chain between the two parameters (see figure 19). But this logic steps from the simple feedback logic, when the rider is required to look ahead, predicting which will be the optimal rolling angle within a discrete time space while imposing the weight motion, not by searching the instantaneous equilibrium, a task undertaken by the steering torque, but instead crating a disequilibrium useful to get more easily the equilibrium in the future. This is a feed forward logic.

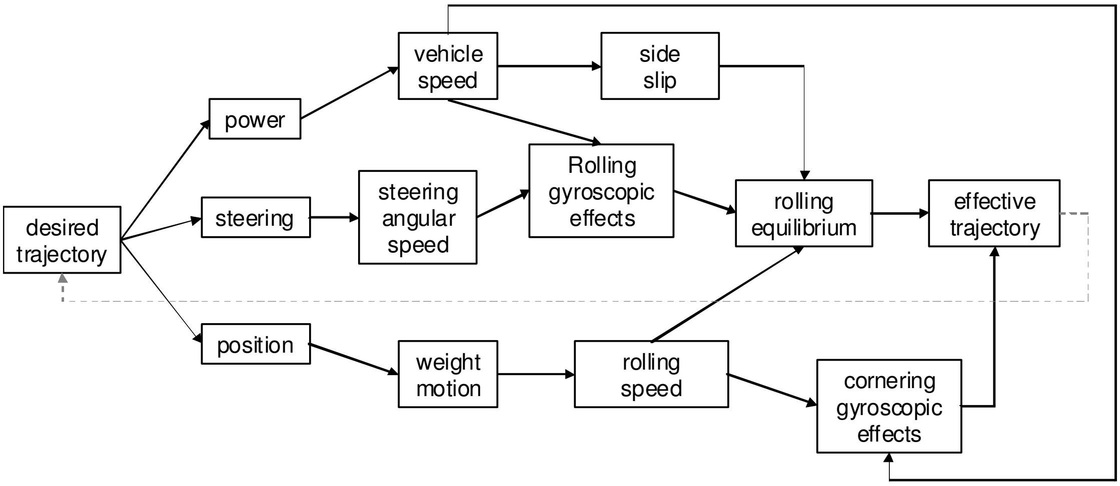


Figure 19. Motorcycle controls conceptual map

6. Analysis of logic controls through kinematics and dynamics

The motion state coming out by matching between the three-dimensional imposed path and the engine features, is compatible with the physical constraints, as asphalt-tires interface grip. This analysis include all internal and external forces over time. A step by step trajectory is described by a discrete array containing plane position, longitudinal and cross slope, curvature radius. Gear ratios, engine torque diagram, braking torques, are indeed other input. Equilibrium between radial forces is tuned by gas level as well as speed increases centrifugal force, while friction is limited because depends only on normal road reactions. The macro "EQ_Fderive (T_m)" performs this task by searcing the friction limit as objective function by tuning gas level.

Longitudinal equilibrium input are current engine torque, whose level depends on the radial equilibrium, current speed, inertias, and current static normal loads on wheels, achievable by imposing a static equilibrium without acceleration. Each time step the macro "EQ_Pitch" tunes, as input the load transfer between the normal road reactions, due to acceleration, in order to get pitch equilibrium is on XZ plane as objective function.

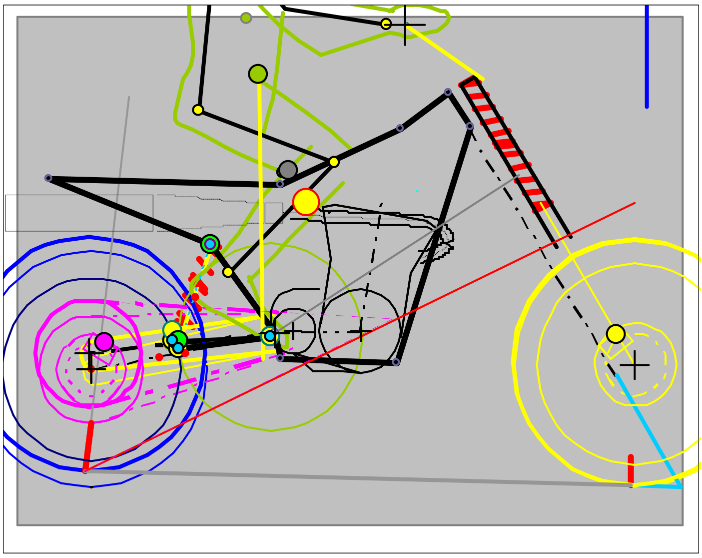
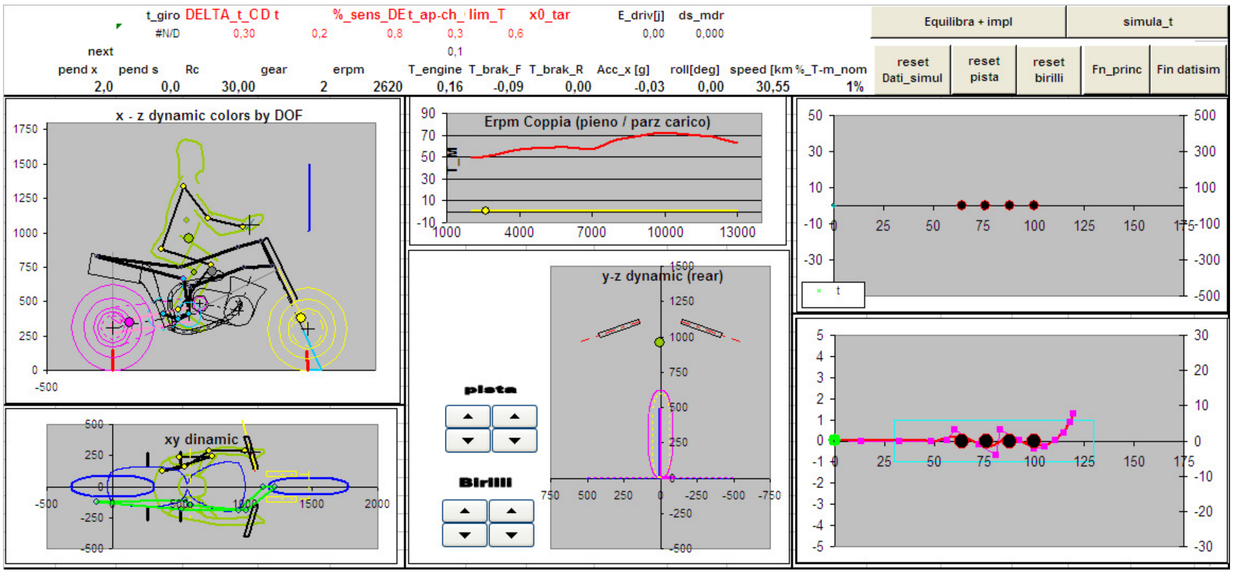


Figure 20. Digital model in dynamic simulation

While friction and centrifugal radial forces are in equilibrium, the system computes the rolling acceleration coming out from rider weight eccentricity, and centrifugal force momentums and inertia, with respect to the rolling axis, which is the line connecting the two contact points on wheels. The rolling angle comes out from the cinematic analysis. The objective function of the macro EQ_roll (Yg), having Yg as input, is the optimal rolling speed to get a desired rolling angle value in the next step. Also an instantaneous analysis could be possible by searching a rolling angle returning the equilibrium between momentums, by tuning Yg. The result is a kind of static equilibrium, but it doesn't work as feed forward logic because it misses a looking ahead strategy, and the results aren't realistic. The gyroscopic effects are separately computed, on both front and rear suspensions. They are transmitted to the entire motorcycle. In particular on front suspension the equilibrium deals with the constraints of handlebar bearing, allowing torque transmission only through any axis orthogonal to the caster one. This is the feature making motorcycles very special machines.

Let have now an overview of simulation windows accessible with the macro. Inside the simulation windows, the tree-dimensional path is described, and the motorcycle position is recalculated each time step, based on the resulting acceleration, limited by engine torque, side grip, rolling and pitch instantaneous angles.



pend x	pend s	Rc	gear	erpm	T_engine	T_brak_F	T_brak_R	Acc_x [g]	roll[deg]	speed [km	%_T-m_nom
2,0	0,0	30,00	2	2620	0,16	-0,09	0,00	-0,03	0,00	30,55	1%

Figure 21. Skittles path simulation window

In figure 21 a path of skittles for slalom test, is defined by joining several Bezier curves: point by point the local curvature radius, calculated by a geometrical interpolation, indirectly affects the engine torque really employed, being centrifugal force the main limit for given speed and side grip conditions. The anthropometric set is very important for dynamic loads computation within the human machine interaction, since the simulation seconds the best possible performance according to trajectory, physical friction conditions, weight distribution of the rider-machine binomial. Output of the computation are the loads that the rider has to afford to equilibrate the handlebar, and weight movement to allow the cinematic performance. When these loads are sustainable by the rider, a neutral driving style is generated.

This simulation works by imposing the trajectory. The optimal one within a real route depends firstly on road surface and other boundary conditions: it is indispensable the direct path knowledge or signalling the specific route characteristics. The optimal trajectory is changing less anthropometric set by anthropometric set, while it changes more driving strategy by driving strategy. The aim was to limit this noise factor, a non controllable parameter, by defining a neutral driving style, got balancing the pure weight use, varying the rolling speed (feed forward strategy) and the front gyroscopic effects use. The gyroscopic effects are not controllable directly with an objective function, searcing the optimal rolling speed by tuning the steering torque: this would be a coarse strategy, returning not realistic steering torque values. Rather a modulation of trajectory is preferred, by inserting some pre-curves with opposite radius, useful to generate the gyroscopic effects due to interaction between steer rotation and front wheel angular momentum, needed to start a rolling effect concordant with the following curve.

A neutral style, not influenced by any predisposition of the rider, is preferred because it represents the best solution for the following optimization: it determines a load history not affected by the noise factors involved in this field: anthropometric dimensions and driving style. Under these assumptions it is possible surrogating an entire population of users by simulating few percentiles with Robust Ergonomic Design (Barone & Lo Iacono, 2011).

7. Improving the software logistic

Understood the need of a neutral style our target is to get it with a sort of neutral simulation, to get by improving and improving the system: the knowledge of the controls and their effect on simulation is the most important strategy to pursue.

On figure 22 the VMEA (variation mode effect analysis) of rider's cognitive path while driving is represented by an Ishikawa diagram. If we think the machine interface as a separate product the rider wants to use, it is possible to figure out the main riding controls as KPC, key product characteristics. Sub-KPCs are characteristics of a system or sub-system affecting the KPC, generally known and controllable. Noise factors are sources of variation causing deviations in KPC. They can be known, unknown, unobservable, uncontrollable (Chakhunashvili, Barone, Johansson and Bergman, 2009).

The items inside the labels are the same of conceptual map on figure 19, but the perspective is different. Here it is shown how the subject driver affords the three main controls (power, steering and position) while driving, taking into account the information coming from outside (vehicle speed, steering angular speed, his proper weight motion). The cause-effect links of the conceptual map (power-speed, steering-steering angular speed, position-weight motion) here changes on a KPC – sub-KPC hierarchies. Within rider perspective, the rolling equilibrium is not a directly controllable parameter (that's why it is yellow highlighted). However can't be considered a noise factor: so it is labelled as a sub-KPC.

According, the remaining factors can be considered noise factors: side slip, cornering gyroscopic effects, rolling gyroscopic effects and rolling speed have all a certain uncertainty under the cognitive perspective, as well as they cant be well predicted (as side slip) or controlled (as rolling speed).All the rider is capable of is to get used to them while learning and utilize the experience in order to stay within safety limits. It is an unconscious robust design process.

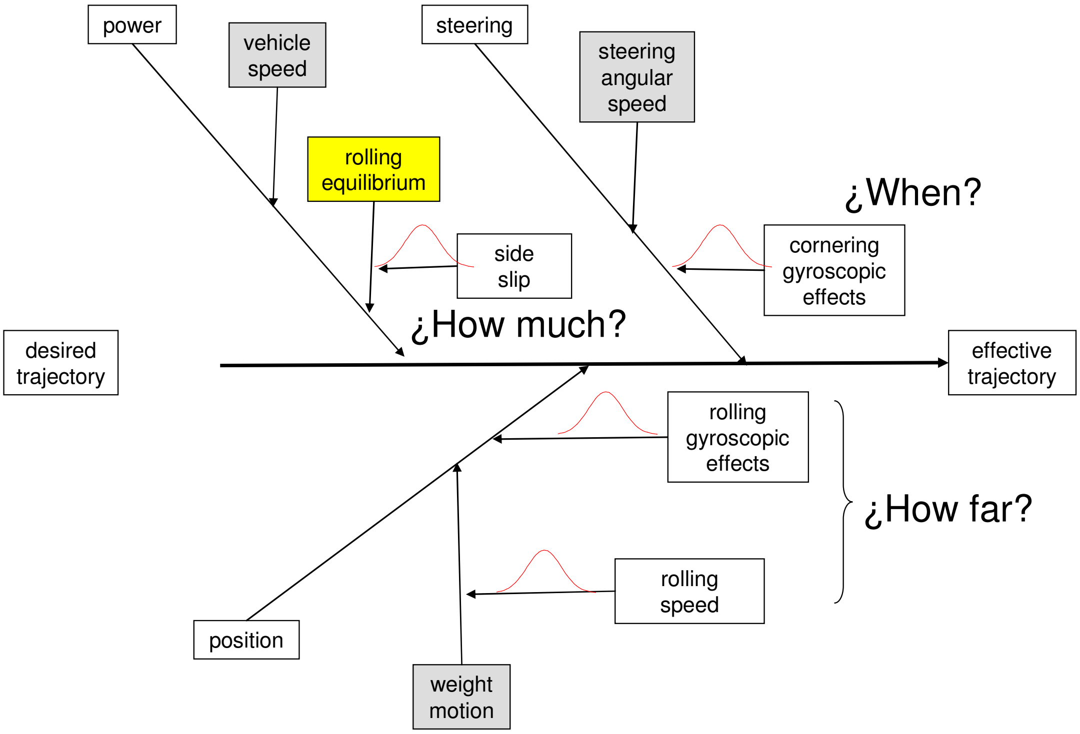


Figure 22. Driving cognitive VMEA Ishikawa diagram

So let analyse under a cognitive perspective the control parameters and the highlighted noise factors, which have to be read as rider uncertainty while expecting the physical phenomenon. Dealing with power supply (that is engine torque) and related side-slip issue, the rider tries to answer to the question: “How much power?”. So the consequently sensitivity analysis has to focus on the variation the power safety threshold limit could be affected by, while this limit is a parameter the rider can set into his mind, according to his experience and knowledge of the riding path boundary conditions. Within a design of experiments (DOE, here done by a computer experiment) it represents a parameter level, while the connected noise factor can be simulated as a normal variation around the fixed level done by a Montecarlo simulation. Figure 23a shows the sensitivity analysis on parameter A level: switching the instantaneous engine torque limit between 30% (A=0, blue line) and 60% (A=1, red line), the slalom simulation changes dramatically. For A=0 power supply is small but constant, as well as cornering speed is low and system is far from side-slip edge. For A=1 acceleration as well as cornering speed is higher, then a dramatic power reduction is required when system gets nearer and nearer to side-slip edge. This physical reading can be achieved also starting from a stochastic analysis: switching parameter A from 0 to 1, being the noise simulated in same way in both levels, a normal distribution of limitations %, N (mu=30% or 60%; sigma = 6%), sensitivity increases as well as parameter level, returning a higher dispersion of engine torque values while increasing the limitation mean value from 30% to 60%.

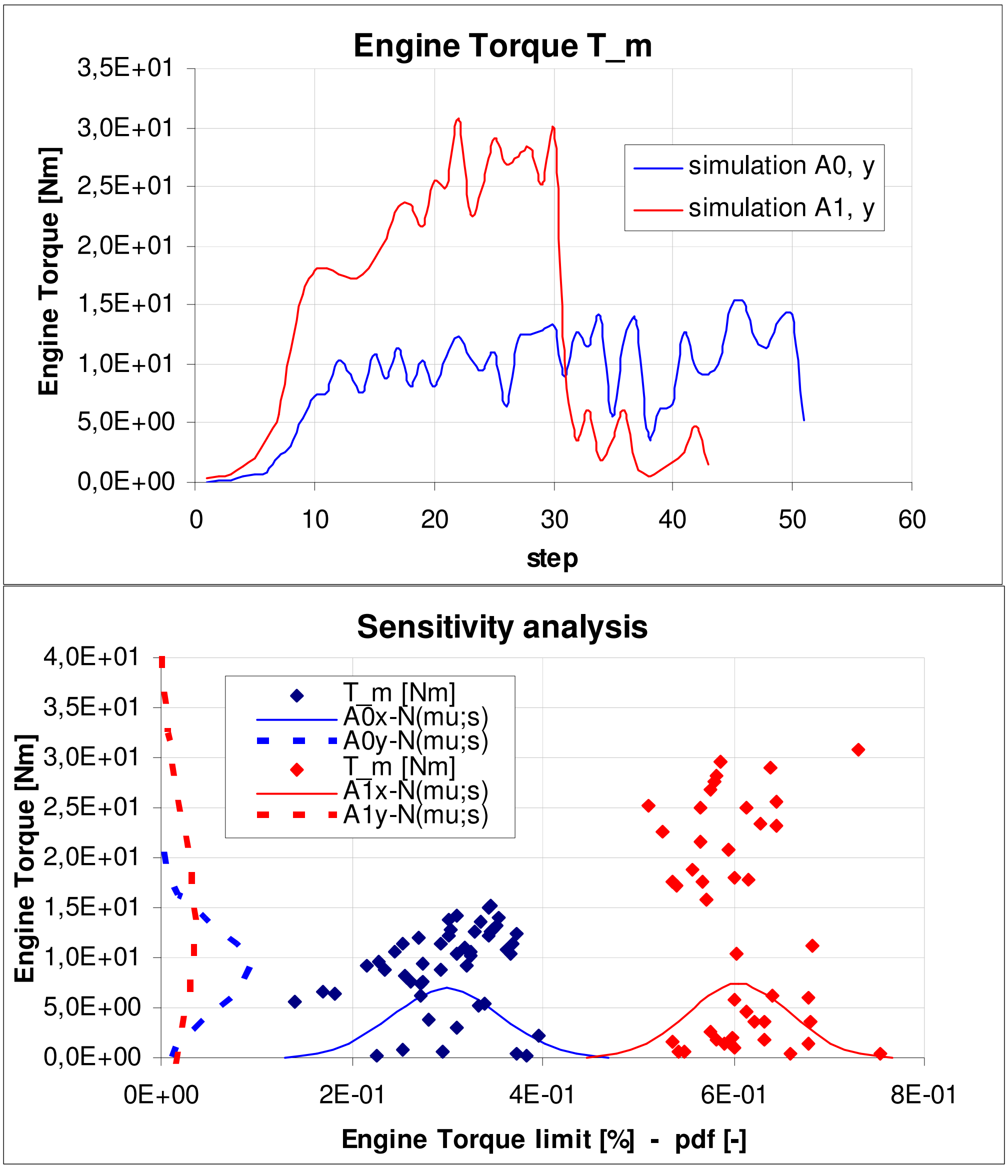


Figure 23a. Power supply control (A) noise factor sensitivity analysis

The power selection is the first operation within the controls sequence, because it is supposed to be orthogonal to the two remaining rider controls. One is the steering action equilibrating the handlebar, loaded by several forces more or less on the rider understand ability. The question for the rider is whether activate steering before weight motion or after it, or, in simple terms "When steering?". According, the corresponding parameter level is an on-off switch between the activation of the control before the weight motion or after. The connected noise factor is the expectation of a cornering gyroscopic effect, coming out from interaction between rolling speed and wheels angular speed (connected to vehicle speed): it can be hardly predicted by the rider, so it brings a sort of uncertainty in the rider decision making process because any steering action can be amplified by this effect, through a critical jaw acceleration until a critical side slip causing a ruinous fall. The simulation of this noise factor is very hard because the simulation consists on an alternation of controls during a time step, so uncertainty over an on-off parameter can bring to parameter switch nullification. So for the moment the steering action noise factor can't be simulated. Figure 23b shows just the effect of parameter B activation order: B=0 simulation steering control is activated before C control (position). Mean value is around zero and standard deviation is almost the same as the two Gaussians show clearly. However the stochastic reading can't overcame the problem of a simulation under transitory conditions. Here the real out put is not the mean steering torque value (it around zero for any slalom test) but its time plot: this isn't a control chart. So the missing overlapping of the two simulations shows clearly that factor B is relevant.

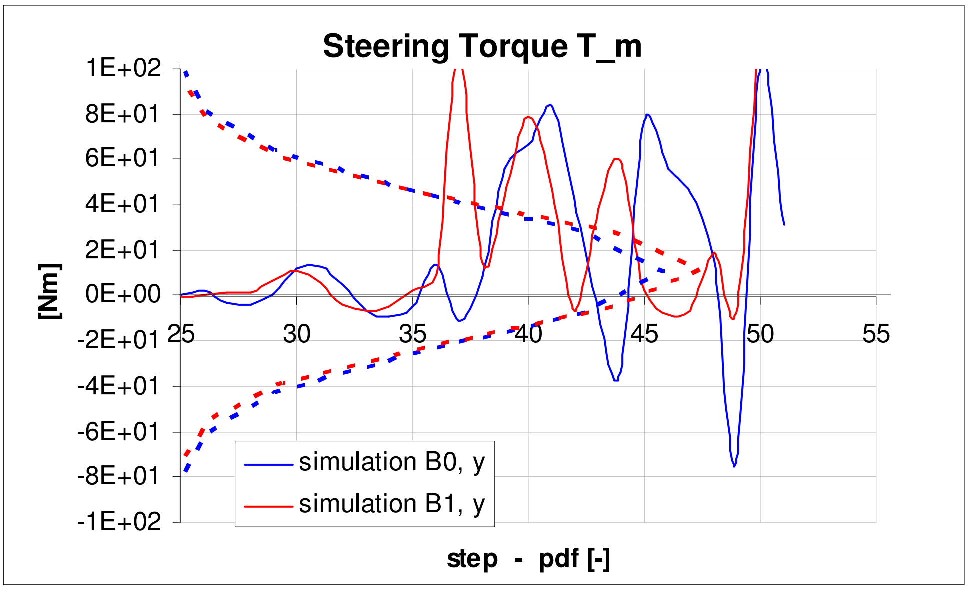


Figure 23b. Steering torque control (B) activation order effect (0 vs 1)

The weight motion can be activated before or after the steering action, according to how explained before, but this first setting depends on previous parameter and doesn't increase the degrees of freedom of the problem, as it will explained later. The parameter C level setting concerns the advance the rider decides to start the weight motion with, according to the feed forward strategy. Remember the objective function of the macro connected to the weight motion control, EQ_roll (Yg) (having Yg as input), is the optimal rolling speed to get a desired rolling angle value in the next step. The uncertainty is caused by expectations of gyroscopic rolling effects and rolling speed. The question is now: "How far to look at?". So as for power supply the consequently sensitivity analysis has to focus on the variation the expected advance could be affected by, while this advance is a parameter the rider can set into his mind, according to his experience and knowledge of the riding path boundary conditions. Within a design of experiments it represents a parameter level, while the connected noise factor can be simulated as a normal variation around the chosen advance level also done by a Montecarlo simulation.

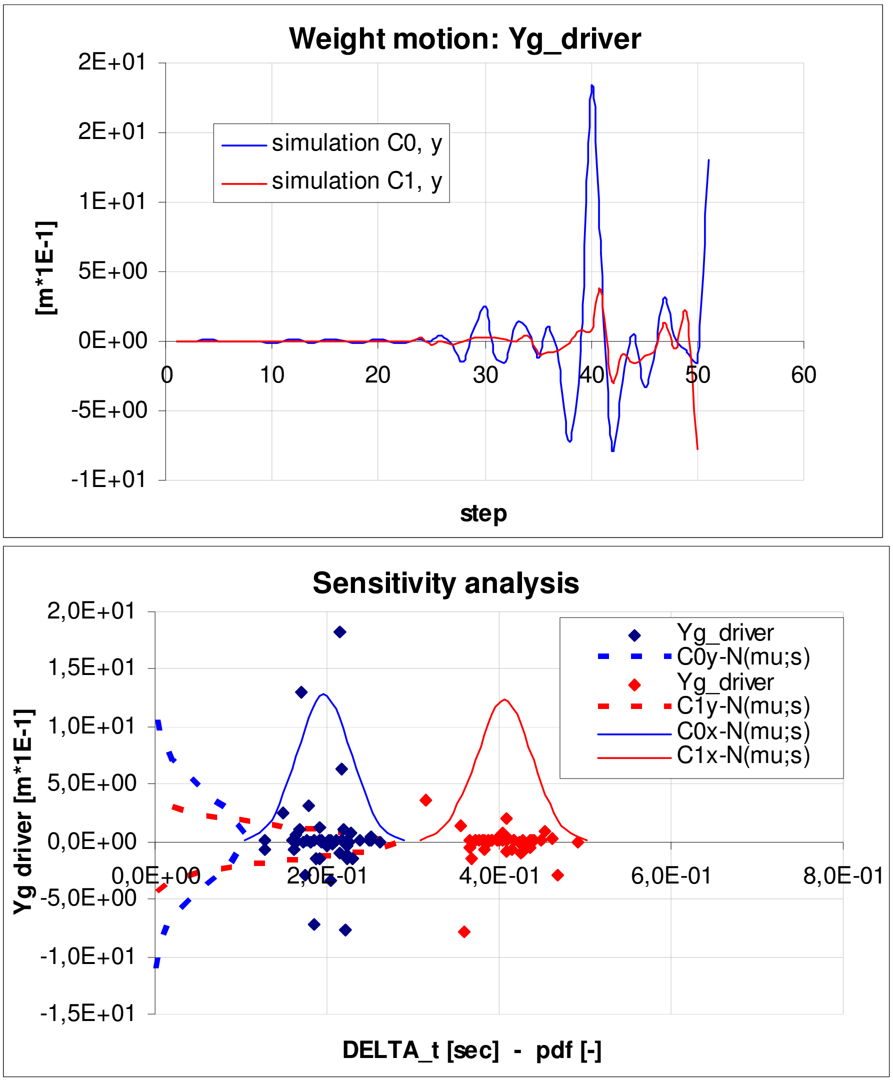


Figure 23c. Position control (C) noise factor sensitivity analysis

Figure 23cshows parameter C sensitivity, being the noise factor simulated in same way for both levels, a normal distribution of advances (that is DELTA_t) , N (mu =0,2 sec or0,3 sec; sigma = 0,03 sec): sensitivity here decreases as well as parameter level increases, returning a higher dispersion of rider body eccentricity values while increasing the advance mean value from 0,2 sec (C=0, blue line) to 0,4 sec (C=1, red line).A physical interpretation could explain the C=0 simulation as a resonance phenomenon, where the lower advance interval triggers a sort of rider overwork. Conversely C=1 simulation returns a very low weight motion, almost unreal. In general a trade off between the two limits is required to be achieved, and that’s the aim of this research.

Once sensitivity analysis had told us system is sensitive to A, B and C parameters values changing, is possible to think on a design of experiments (DOE), where introducing them. Having the three parameters two levels each, a full factorial DOE would require $2^3=8$ trials. A computer experiment can easily support to afford them, so a general factorial 2^{3-0} DOE has been done, described on table 4. It is possible also (under certain conditions) try to verify the conclusions for a fractional factorial, by selecting the trials.

Table 4.Driving cognitive parameters DOE (O.F.A.T.)

Factor	A	B	C	Y1	Y2	Y	VAR	interact 2	A up|	B up|	C up|	Pareto Esti	SORTED	NPP
Descr.	Tm_lim	Tst_act	Dt_adv	En_dr	En_dr			1	2,8E+04	0	0	ABC	2,4E+03	2,0E+03
Level 0	0,2	before C	0,2					2	1,8E+04	1	0	AB	2,5E+03	4,3E+03
Level 1	0,4	after C	0,4					3	1,9E+02	0	1	B	5,3E+03	6,1E+03
Dim/set	%	[-]	[sec]					4	7,7E+01	1	1	BC	5,5E+03	7,6E+03
1	0	0	0	3,4E+03	9,8E+03	6,6E+03	2,1E+07	5	0	-6,0E+03	0	AC	1,1E+04	9,2E+03
2	1	0	0	2,0E+04	4,9E+04	3,4E+04	4,1E+08	6	1	-1,6E+04	0	A	1,1E+04	1,1E+04
3	0	1	0	3,2E+02	9,1E+02	6,2E+02	1,8E+05	7	0	2,4E+02	1	C	1,5E+04	1,3E+04
4	1	1	0	3,1E+04	6,3E+03	1,9E+04	3,0E+08	8	1	1,3E+02	1			
5	0	0	1	4,5E+01	6,0E+01	5,3E+01	1,0E+02	9	0	0	-6,5E+03	MEAN.EF	7,6E+03	
6	1	0	1	3,5E+02	1,3E+02	2,4E+02	2,3E+04	10	1	0	-3,4E+04	SIGMA.EF	4,9E+03	
7	0	1	1	4,3E+02	1,5E+02	2,9E+02	4,0E+04	11	0	1	-3,3E+02			
8	1	1	1	1,9E+02	5,5E+02	3,7E+02	6,4E+04	12	1	1	-1,8E+04			
A	1,1E+04	-2,5E+03	-1,1E+04	a	8	S_a^2	9,1E+07	interact 3						
B	-2,5E+03	-5,3E+03	5,5E+03	T	2	S_effect^2	2,3E+07	med[(-,-,+);(+,+,+);(+,-,-);(-,+,-)]			8,8E+03			
C	-1,1E+04	5,5E+03	-1,5E+04	N	16	SIGMA_cp	4780,72	med[(+,-,+);(-,+,+);(+,+,-);(-,-,-)]			6,4E+03			
ABC	2,4E+03			GRAN.AV	7,6E+03									

The design is complete as well as all possible combinations of factor levels are experimented; symmetric by all factors having the same number of levels; balanced on trials since for each experimental treatment, the same number of trials are made: in this case they are computer experiments replications. Design balancing brings ortogonality and minimum variance of estimated effects. A and C factors are quantitative variables while B is a categorical variable. Big Y is in this case the energy the rider has to spend when affording the slalom test: as shown on figure 10, this indicator directly depends both on steering torque (factor B) and weight motion (factor C); indirectly it depends also on vehicle speed, controlled by factor A, because A and C are affected by speed. The analysis of DOE brings out a numerical evaluation of both main effects (A, B, C) on big Y, and interaction ones (AB, BC, AC, ABC). A rank of these seven effects is shown on Pareto diagram of figure 24: C effect is dominant, and a physical explication is also available. The manoeuvre advance Delta_t, representing C parameter determines a different body motion amplitude, and weight moving against centrifugal force is quite energy wasting. Steering torque also affect energy, but the equilibration of front end dynamics doesn't vary on B parameter (activation order) as much as C parameter (weight motion advance control).

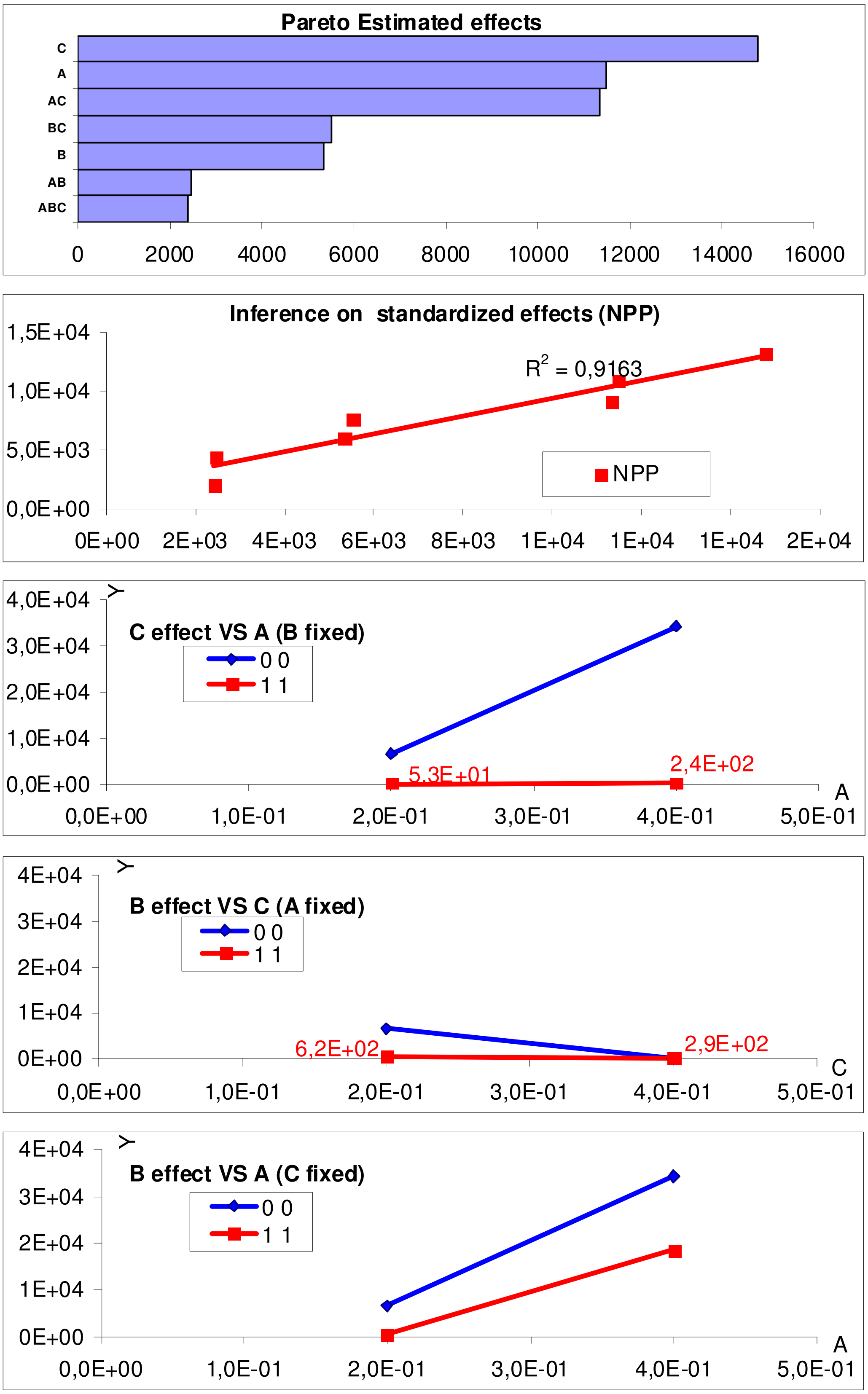


Figure 24. Driving cognitive parameters DOE (O.F.A.T.)

Control A is second must important factor because A controls acceleration and speed, affecting in turn centrifugal force. Parameter A and C combination effect is high and it is evident also on third graph of figure 24, where the interaction between A and C is highlighted by different slopes of the segments Y(A, $\underline{B}$, $\underline{C0}$) blue, and Y(A, $\underline{B}$, $\underline{C1}$) red, where, being B at same level $\underline{B}$ for both lines, C changes level on second line, bringing a different slope, both positive, so the interaction is positive. Same analysis has been done for BC and BA effects, where two positive but much lower interactions can be observed.

8. Software calibration control

Once control effects have being estimated within mathematical simulation, and software is proved having its consistency, the system needs also a calibration using real numbers coming from an experimental section, in order to control the results.

The simulation here presented is based on mechanical deterministic equations, so it needs just a data setting for friction coefficients, by experimental calibration. Friction comes out on the asphalt-tires interface, on steering torque application, and in rider-motorcycle contact surfaces. There is also the power transmission linkage friction, but handling rear wheel torque diagrams makes it unnecessary. For friction on front and rear suspension mechanism, it’s rather preferred to speak about “damping”, a controlled and optimized friction, which is specifically studied by the pitch equilibrium section.

Between tires and asphalt there is a rolling friction in longitudinal sense, and a static one inthe lateral one, the side grip. First issue setting is not required, because rear wheel torque data are supposed to be used, and this kind of torque already takes into account this power loss (neglecting the noise factor of the surface matching with the rear wheel).

Side grip is not required to be set, if during experimental section, friction limit is not reached, neglecting little slide phenomena: here centrifugal and friction forces are in equilibrium (see equation (a)), so computed the formers by simulation, the latter results to be detected.

Neglected the effects of bearing friction, the steering torque application requires, due to caster offset,an add side static friction on front wheel, contrasting the manoeuvre including a torsion grip: the contact point is, as a matter of fact, like a pivot, contrasting the steering action, in turn equilibrating front wheel dynamic effects (also gyroscopic ones). The overlapping of these three effects, easily separable in theoretic line, makes compulsory an experimental check of the steer force levels.

Finally, the rider-machine contact surfaces friction, generates sometimes rider energy wasting, and sometimes a really good help as well as an add constraint. Nevertheless these aspect doesn't concern directly posture problems, and so they are not investigated within this research. The calibration problem will be focused so on steering forces and general likelihood of the dynamic simulation, concerning the time matching between rider weight motion, rolling angle, steering angle and steering force.

Skittles slalom

The best simulation condition, as well as the most comprehensive of all the effects, like steering torque in combination with lateral motion as main driving strategy under the feed forward logic, is the slalom test, universally perceived as the "handling test".

The slalom test is a joint of several transitory conditions. The turning series is afforded with repetitive commands, as rider weight motion to the curve inner and steering torque to extern, with amplitude and frequency linked to the vehicle speed and to pin distance. Nevertheless these commands series is different from the one used to steady afford separately same radius curves: the rider, having the view of the entire trajectory by seeing all the pins, while equilibrating the steer to turn on the former skittle, anticipates the manoeuvre to afford the latter one, by moving his mass centre. Here the feed forward strategy application is strongly required, because with a simple series of steady states (rolling momentums equilibrium by tuning weight offset step by step) the rider is not able to perform the trajectory.

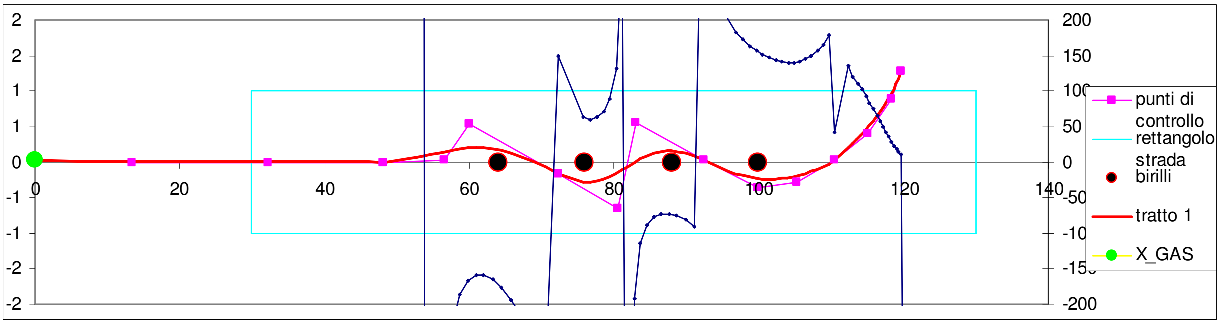


Figure 25. Trajectory imposed on a Skittles path

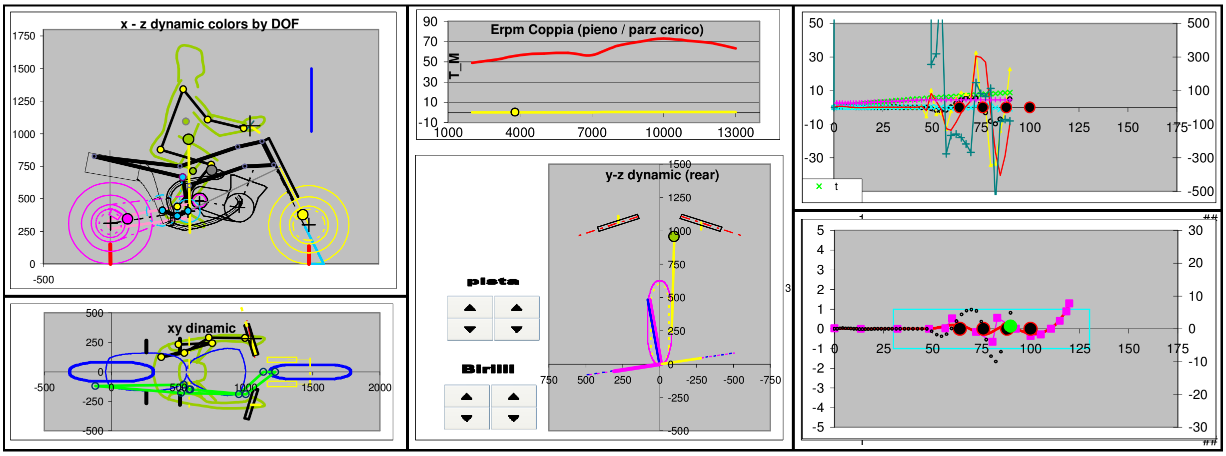


Figure 26. Simulation window on skittles path at end simulation

On the graph “y-z dynamic” of figure 26 is possible to follow the relative roll, with the two normal lines blue and pink in the contact point, the former representing the real normal road and the latter representing the normal gravity: they are not parallel if there is a transversal slope. Also mass centre position is highlighted (green point), being its offset capable of rolling instantaneous speed controlling. There are also the vectors indicating steering forces on the handlebar and lateral derive forces in both wheels, when arising if centrifugal forces overcome the side grip. When the two forces are discordant, a jaw motion starts.

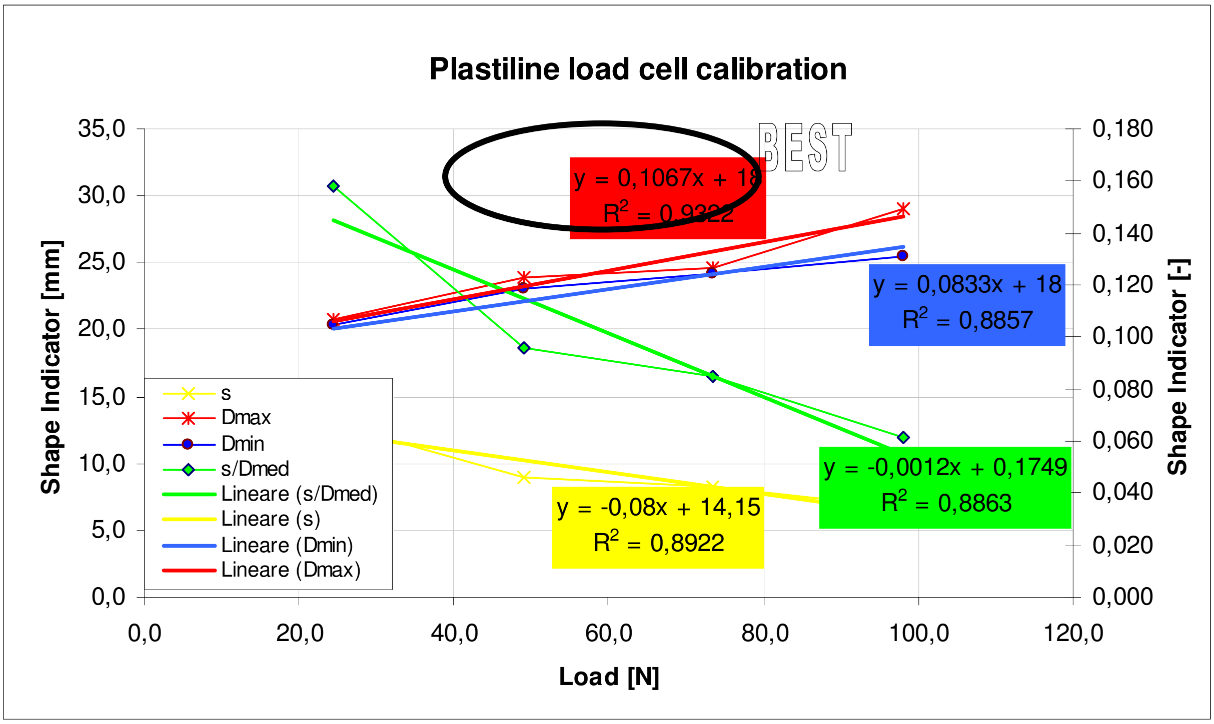


Figure 27. Plastiline load cell calibration

The slalom path the system is calibrated with, shows a trajectory starting with a pre curve, (right hand), and then a sequence of three curvature positivity changes. For the calibration an acquisition of rolling angle and steering angle has been done by filming two simultaneous 24 frames per second synchronised sequences, allowing a cinematic validation. In order to evaluate the force level on the steer, a calibrated plastiline load cell has been used: it is a simple plastiline ball having a calibrated diameter before load charging while a different shape after. Calibration is shown on figure 27, where several indicators (maximum and minimum diameter, thickness, thickness-medium diameter ratio) have been correlated with the real load, returning a more or less linear response. The chosen indicator has been the maximum diameter, being the R-square indicator the higher the best.

Figure 28. Calibration test bike wiring

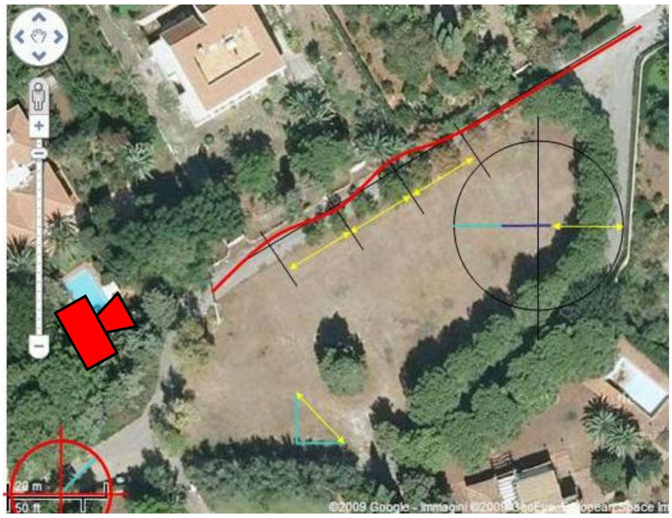


Figure 29. Calibration test trajectory building by Googlemaps ®

Figure 30. Calibration reliefs (roll and steering angles timing)

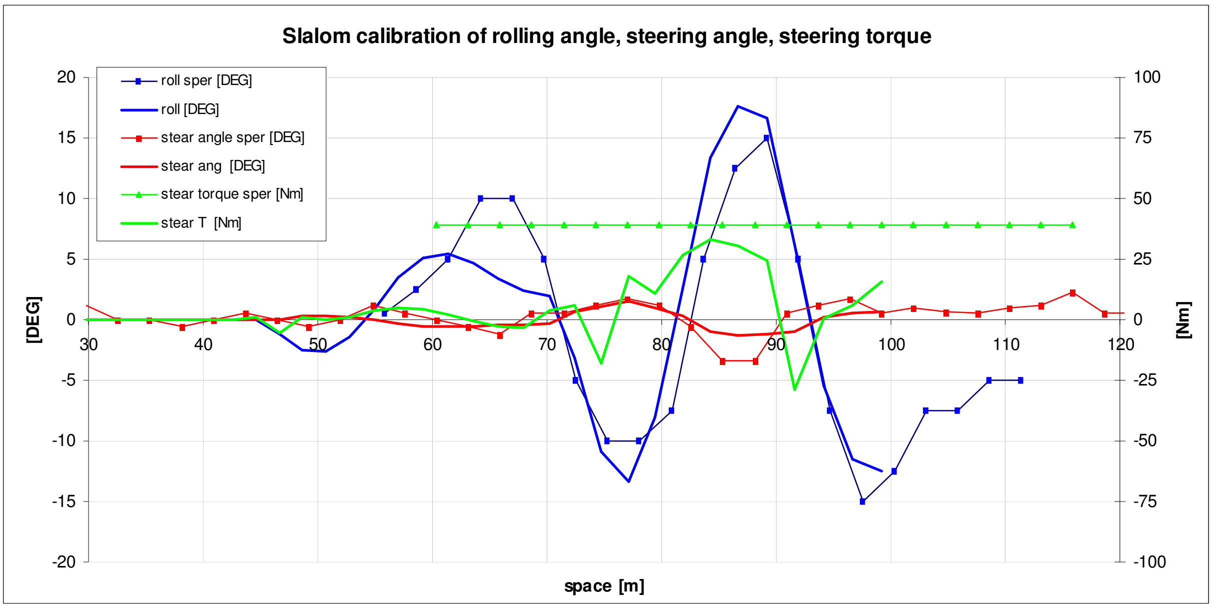


Figure 31. Calibration output data (roll and steering angles timing)

The results are shown on the graph of figure 31. Steering angle (red plots) always anticipates the rolling angle with half period and has same frequency. First good result is a simulation providing a good prediction of experimental outputs, under both quantitative perspective and time phase. Lets analyze the results in a qualitative way. A middle size touring bike has been used Honda CBF 600S of figure 2: stability is preferred rather than handling. So a heavy front weight is required since inertias help in this direction. According, lower steering angles are required in usage, because front suspension geometry has to be as much stable as possible, then a narrow handlebar is preferred. In an other hand the touristic posture, with arms line incident with the steering axis, doesn't allow a weight motion simple effect, like on race track motorcycles, where alignment of arms with forks helps weight motion without big steering component. Then in touristic motorcycles a weight offset starts also a steering component. There is actually combined effect: in most of cases the weight motion starts by pushing the correspondent side of the handlebar, generating high gyroscopic effects due to front inertias. This effect helps an according rolling motion so at the end a limited weight offset is required, also helped by gravity. But the force level equilibrating the gyroscopic effects is high because of the narrow handlebar, and using the weight to equilibrate this force is a good way to save energies. So despite a small mass offset, the weight is utilized to contrast the handlebar in longitudinal direction: there is a suspension state for an instant. All these circumstances determines the tendency to drive these kind of motorcycles(touristic) by hinting a weight motion while charging the correspondent side of the handlebar (inner side of the curve) and waiting the gyroscopic rolling effect. This attitude affects also the trajectory by inserting a little opposite pre-curve before the real curve, effect of the first discordant steering action.

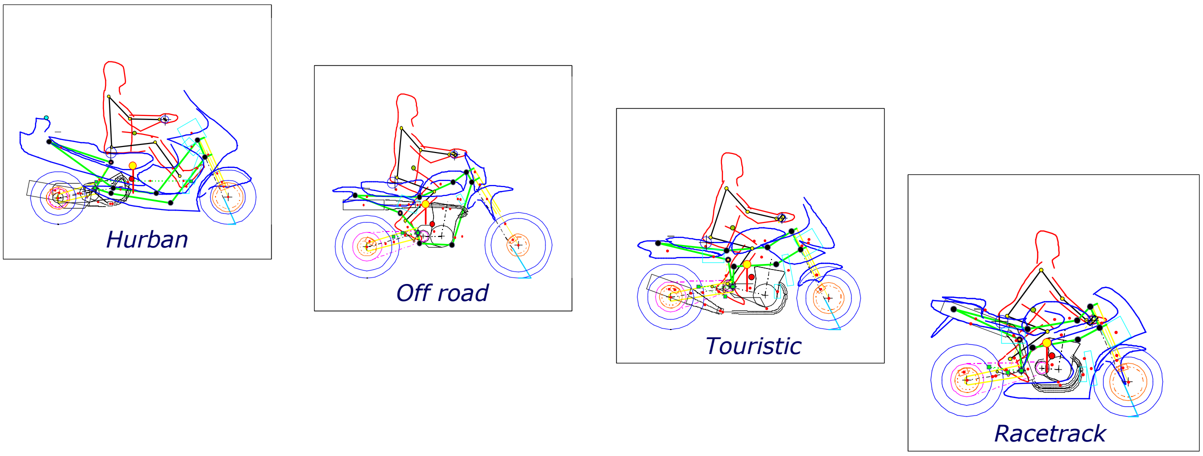


Figure 32. Motorcycles and related postures

For this feature also a constraining tank allows equilibrating the handlebar torque reaction on the rider. A touristic posture is a trade off between simple weight motion effect of racetrack motorcycle, as will be better explained later, and a simple handlebar driving effect of big urban maxi-scooters where weight motion always induces a steering rotation because of arms position, but with limited effects due to reduced inertias on front wheel, due to a smaller wheel radius, and a lower speed: in this kind vehicles the steering driving effect is preponderant, and stability is manoeuvred. In the maxi-scooter the steering force is rather an arm traction on the external side of the curve, by hanging on the external side of the handlebar, rather than pushing on the internal one, with the same effect in terms of steering torque. By the way the trigger is always an opposite pre-curve, but weight motion effect is predominant over the gyroscopic effect.

9. Racetrack simulation

The same analysis can be performed on a real racetrack. The one on figure 33 has been chosen to make a second validation of the system.

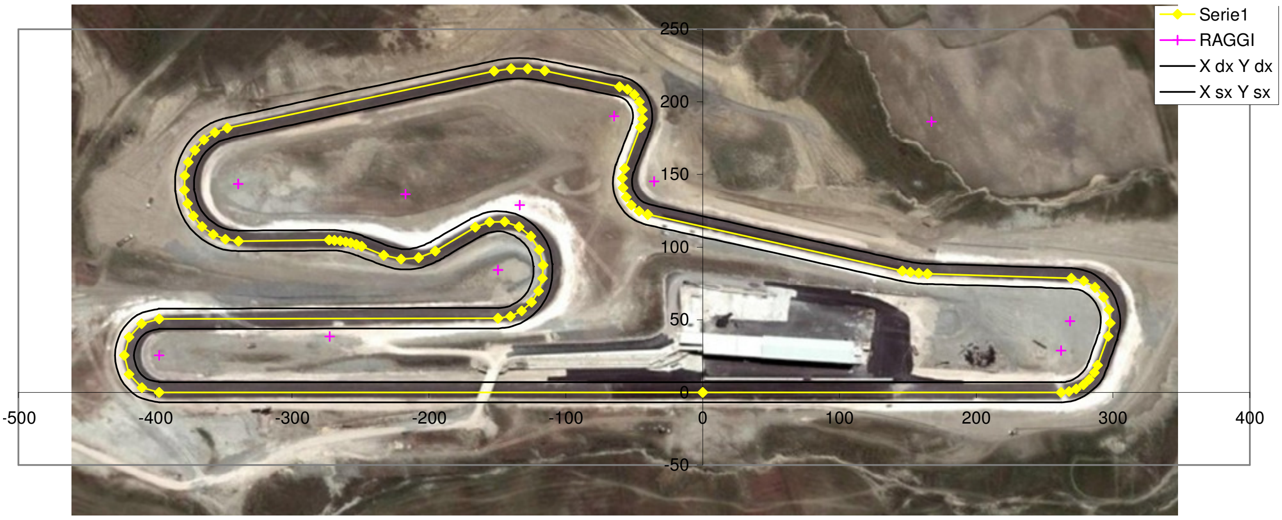


Figure 33. Satellite relief of "Valle dei Templi" track by Googlemaps ®

The track has been digitally reproduced using satellite picture and terrestrial reliefs concerning local slopes (figure 34). The parametric path has been then placed within the track borders: the graph of figure 35 shows how the modularity of control polygon helps drawing an efficient trajectory by using a simple mathematical model. The violet points are a localization of trajectory curvature centres per each single slot. The trajectory local curvature centres are localized near the track ones

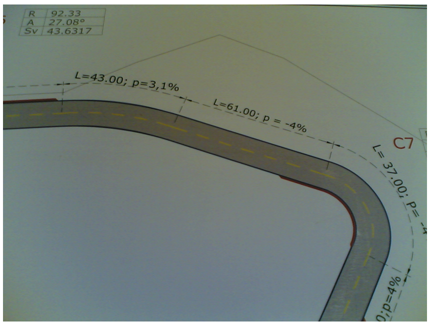


Figure 34. Curvature relief detail of "Valle dei Templi" track by Googlemaps ®

when the rider follows the middle line. A dedicated algorithm, in order to allow understanding the motorcycle position within the slots, has been developed, based on covered distance and local tangent to trajectory. A refine positioning then is done by interpolation. Obviously an efficient trajectory has to follow the objective of riding time reduction, achievable by a trade-off between two criteria: first distance reduction (keeping track inner line) and second the speed increase (keeping external line of curves): sometimes they agree, sometimes they don't. By the way the direct experience is irreplaceable since it is fundamental the knowledge of the local imperfections, so considering an a priori parameter the optimal trajectory is preferred, while man-machine binomial is the object of the optimization. Also the optimal trajectory depends on the motorcycle type: for example a two strokes 250 cc. has a speed cornering totally different from a four stroke 1000 cc one. And optimal trajectory changes less by changing anthropometric set (body size by body size), while it changes more driving style by driving style: the definition of the "neutral driving style", is an attempt to limit this noise factor, by balancing the pure weight motion strategy, controlling rolling speed, and the usage of front wheel gyroscopic effects, by inserting pre-curves within trajectory, to generate an interaction between steering and front wheel, returning a rolling action.

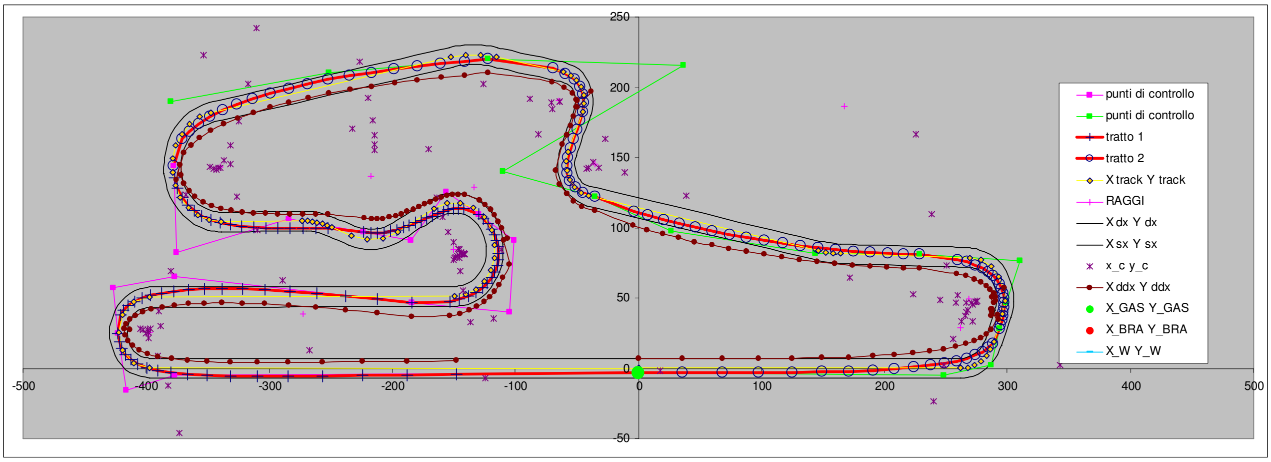


Figure 35. Trajectory building (red line) on "Valle dei Templi" track

The curvature instantaneous radius graph is reported on figure 36, and a local zoom on detailed graph: the critical points are the second order trajectory discontinuities, or inflection points, where the radius jump from plus infinite to minus infinite or vice-versa, because this changing addresses several position detecting problems.

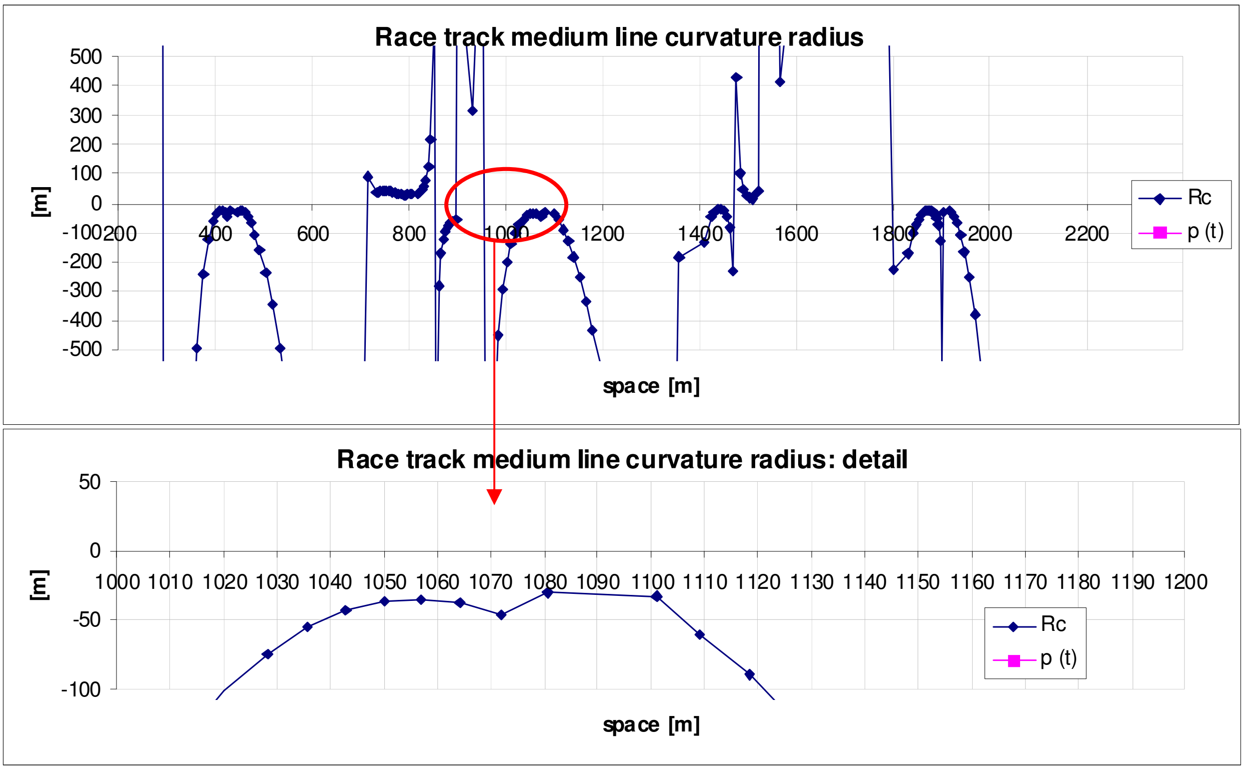


Figure 36. Trajectory curvature radius on "Valle dei Templi" track

Minimum points of curvature radius absolute value of figure 36, localize the highest centrifugal force conditions. The software provides the driving logic acquiring this information in advance, preparing the manoeuvre to equilibrate this centrifugal load.

The digital mock-up utilized for racetrack simulation is a Triumph Daytona 675, whose constructive dimensions have been relieved for the ergonomic matching. The total loss function is 5.26 doubled respect with the touring CBF 600 of the slalom calibration, using the same anthropometric set (set n. 2, man 50th percentile).

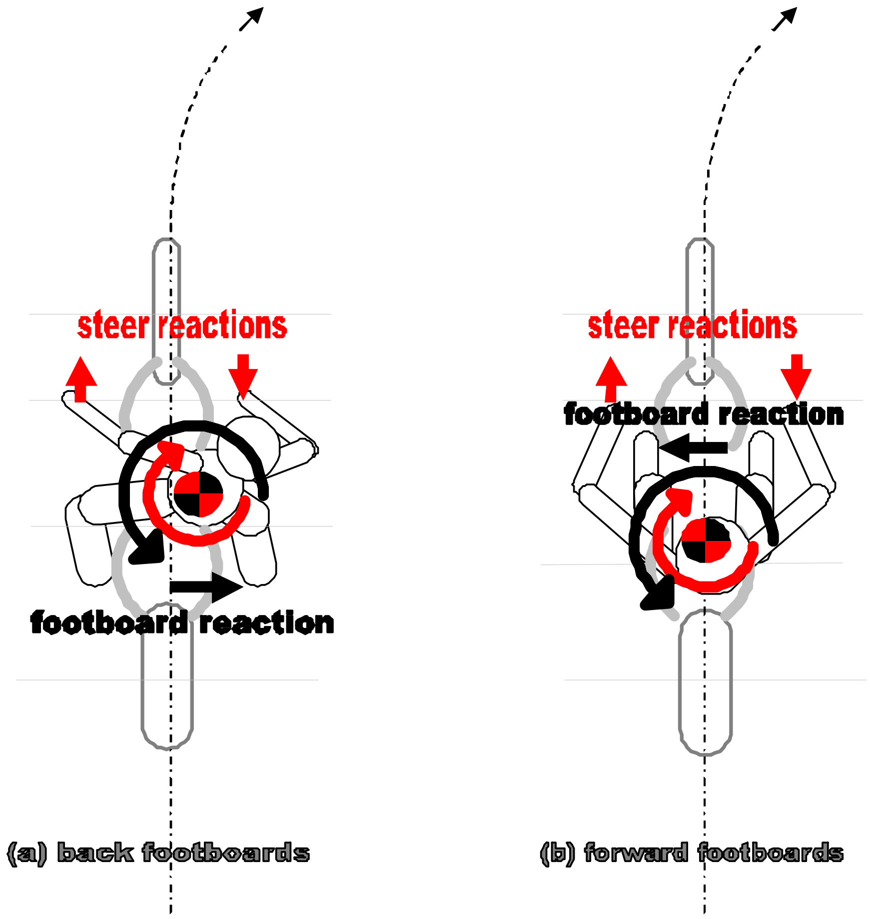
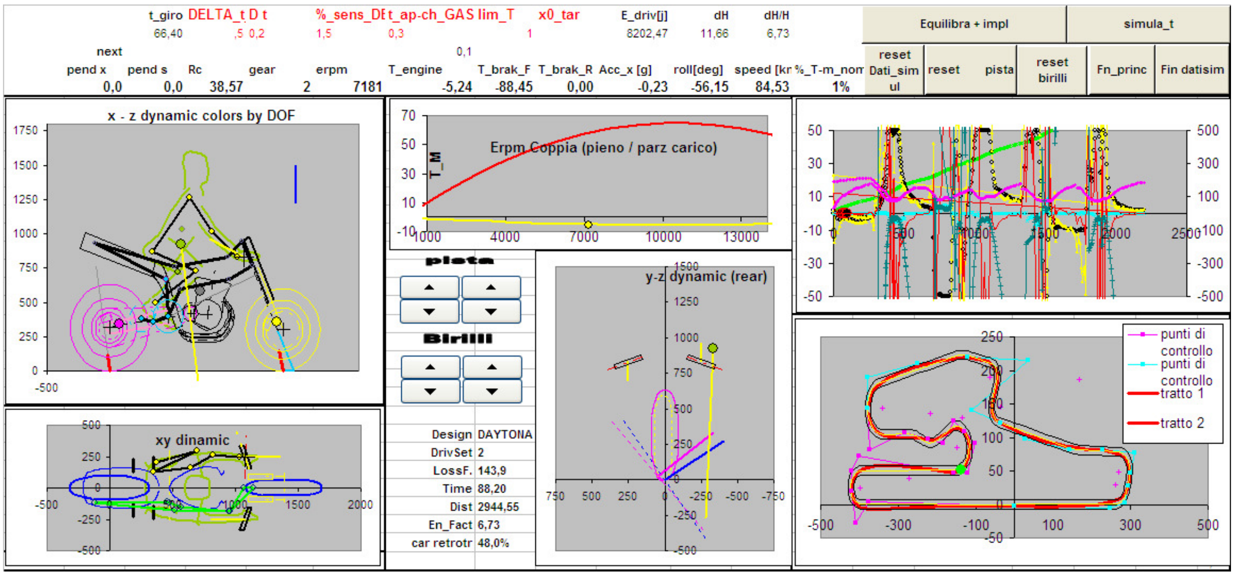


Figure 37. Driver rotation equilibrium: (a) backward footboards; (b) forward footboards

A racing motorcycle imposes a very low handlebar in order to ideally align arms and caster, while braking and then cornering: the more is the rolling effect the less the turning one, due to the limited arm force component, orthogonal to steering axis. In this type of motorcycle better providing footboards behind the driver mass centre. Internal driver body torsional equilibrium on baricentric driver axis requires an opposite reaction: better the inner curve foot pushing to external side (if footboards are backwards), than external foot pushing to inner side (if footboard forward), see scheme on figure 99. First solution (fig 37a) brings as a secondary effect the posture imbalance through the inner curve, good characteristic while driving near the limit. Moreover the seat material can be smoother, since a certain bottom sliding is required: no torso action equilibrating torsion is required to this interface part! While the footboards have a forward position, the required reaction is neutral with respect to posture (fig 37b), and so fit for relaxing ride, waiting for gyroscopic action (see previous section).



t_giro	DELTA_t	D t	%_sens_DE	t_ap-ch_GAS	lim_T	x0_tar	E_driv[j]	dH	dH/H
66,40	,5	0,2	1,5	0,3		1	8202,47	11,66	6,73

next 0,1

pend x	pend s	Rc	gear	erpm	T_engine	T_brak_F	T_brak_R	Acc_x [g]	roll[deg]	speed [kr	%_T-m_nom
0,0	0,0	38,57	2	7181	-5,24	-88,45	0,00	-0,23	-56,15	84,53	1%

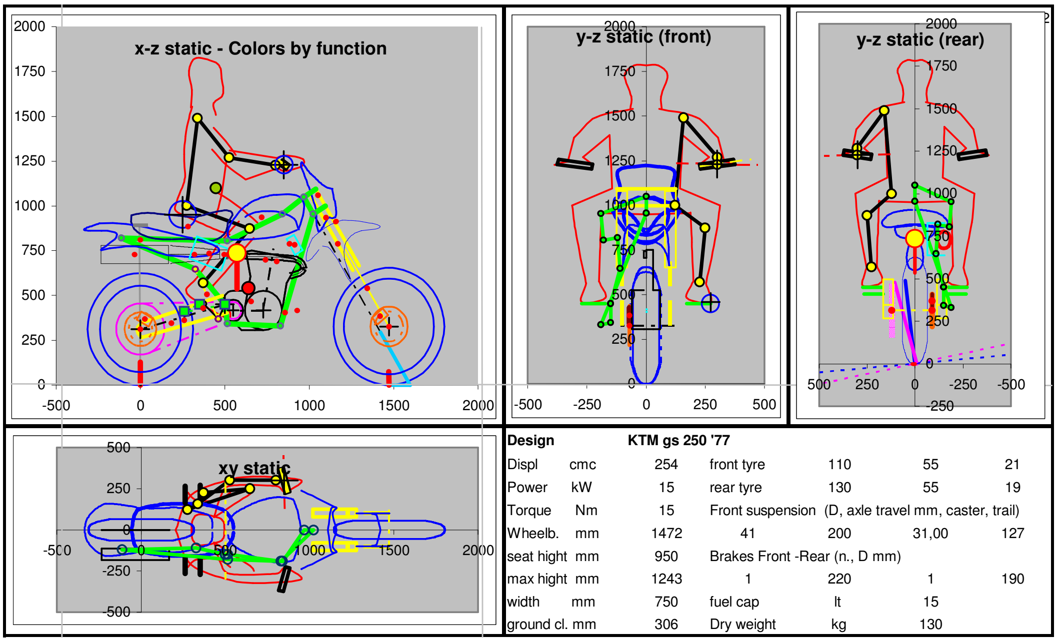
Design	DAYTONA
DrivSet	2
LossF.	143,9
Time	88,20
Dist	2944,55
En_Fact	6,73
car retrotr	48,0%

Figure 38. Simulation window "Valle dei Templi" track

The dynamic performance is shown on the figure 38. The time achieved in a simulated round, utilizing the known trajectory, is very realistic, compared with the experimental data coming out by the transponder. From the starting point the racetrack performance could be optimized by choosing the correct gear ratios, or in order to performan evaluation of all the loads coming out within a high mechanical stress situation, in order to dimension any item for a very specific usage.

Track simulation for Items optimization

The computational method simulating the dynamic behaviour of the vehicle along a specific path allows also to identify the loads stressing specific motorcycle items as frame or suspensions. For this reason the software needs, beside the input shown before, information about the frame material, stiffness and damping coefficient for suspensions. The figure 39 shows the input screen for 1977's KTM Penton 250. Beside the motorcycle geometry, data simulation input include the imposed 3D trajectory, friction coefficient for tires-asphalt contact and rider's anthropometric data.



Design		**KTM gs 250 '77**				
Displ	cmc	254	front tyre	110	55	21
Power	kW	15	rear tyre	130	55	19
Torque	Nm	15	Front suspension (D, axle travel mm, caster, trail)			
Wheelb.	mm	1472	41	200	31,00	127
seat hight	mm	950	Brakes Front -Rear (n., D mm)			
max hight	mm	1243	1	220	1	190
width	mm	750	fuel cap	lt	15	
ground cl.	mm	306	Dry weight	kg	130	

Fig. 39. Off road motorcycle for structural optimization

The simulation for this motorcycle model has been done in this case along part of the path shown on the figure 6, with one right and one left curve.

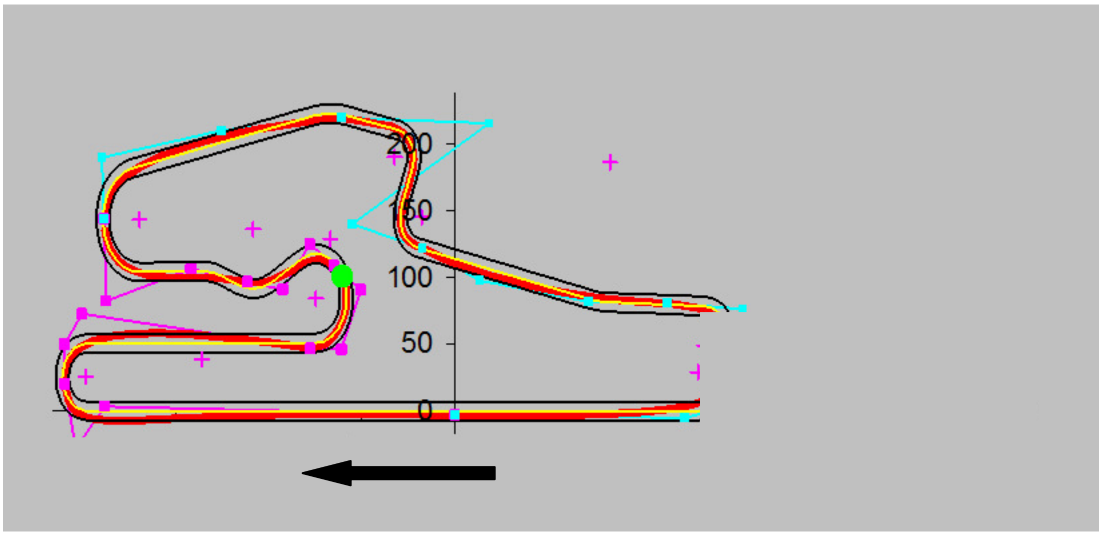


Fig. 40. Motorcycle localization within dynamic simulation

The vehicle starts in the main rectilinear and when an almost 100 km/h speed is reached, suddenly a deceleration due to the braking torque application on the front wheel is imposed. Then there is a right turn, and, after a second rectilinear, there is the left curve. “Progetto Motocicletta”, returns speed, roll, braking diagrams. In the reference system, united to the motorcycle, x axis is longitudinal, while a cross plane having the normal reference N of the road, including the cross slope point by point, is utilized to calculate the friction forces in lateral equilibrium (see figure 41).During the simulation the rider can tune the value of mass centre offset with the motorcycle sagittal plane, with a step by step feedback logic, in order to try to achieve an optimal rolling speed, which is calculated in order to keep the rolling equilibrium in riding. This dynamics works as well as equilibrium forces on the handlebar are provided by rider, while lateral derive forces arise when inertias overcome the top grip loads the road and the tires can exchange. When these forces in front and rear wheels are discordant, a yaw motion starts. To avoid derive forces an engine control cuts the torque level.

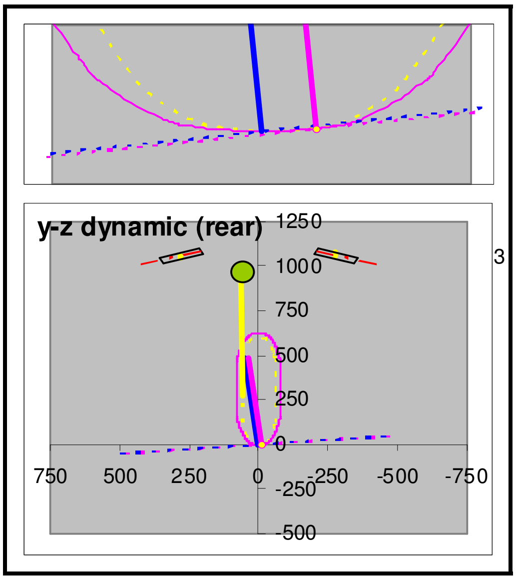


Fig. 41. Tire-road contact point simulation

The graph in figure 42 shows two acceleration phases. When the speed reaches almost 100 km/h value, a braking torque provide a deceleration to 60 km/h. The braking is linked to the corner entry: the roll angle diagram shows an up grade to the 53 deg, corresponding to the central part of the curve. Then roll come back almost to zero during the rectilinear between the two curves. The left curve shows the same attitude of the right one, but with a negative roll, as the curvature radius is opposite.

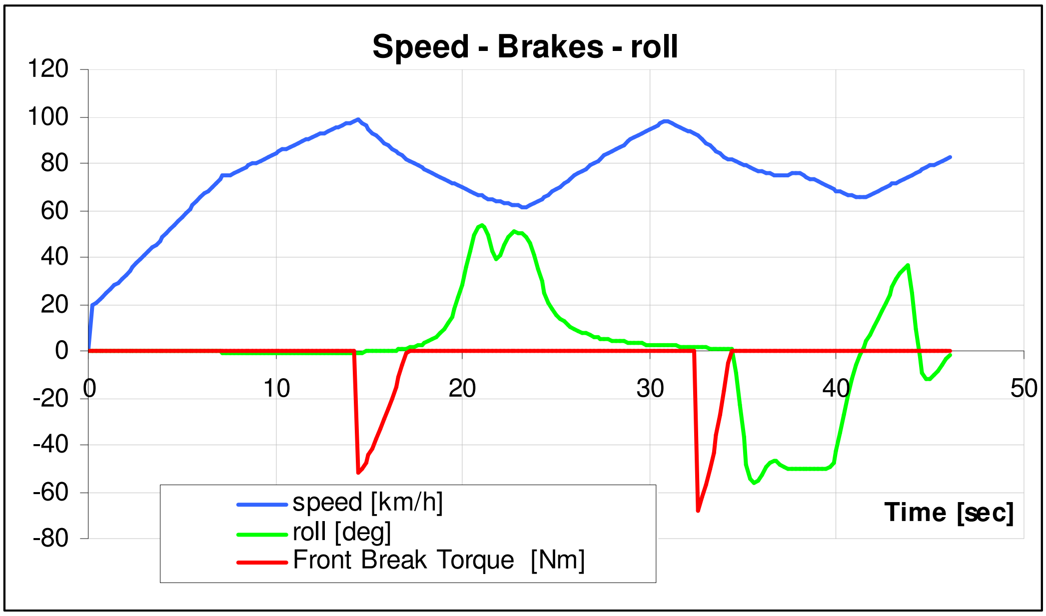


Fig. 42. Speed, braking torque and roll diagrams during simulation

The normal reactions on front and rear wheels, correspond to different phases of the circuit. Suspensions geometries filter the components transmitted to the frame. In the front one there is a component alongside the caster axis, and one orthogonal. In the rear one the global force has components both in the dampers upper axis, linking the dampers with the frame, and in the main axis of the swing arm.

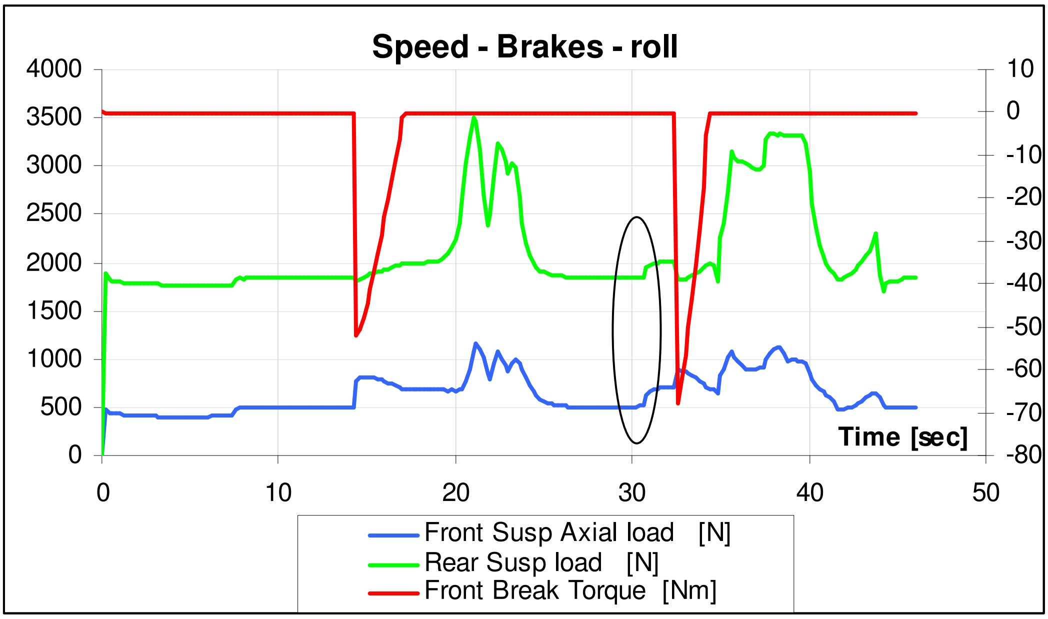


Fig. 43. Braking torque and suspension forces diagrams during simulation

Figure 43 shows the diagrams of the loads on front and rear suspensions. The braking torque time history makes easy understanding: during the braking phase a load transfer shows up between front and rear wheels, with an increment in the front suspension, especially in the second curve, near the maximum absolute value of braking torque.

The braking action stops and the cornering determines a new distribution of forces, which at the beginning have values similar to the ones during the rectilinear part, but then they arise new higher levels, both in the front and in the rear suspensions, because of inertial forces arising and consequently upper loads on the interface between asphalt and tyres, according to lateral equilibrium.

The cutting force on the front fork shows a sudden rising of the value, during the braking,to the maximum of 806 N.

10. Conclusions

This work has the objective of providing a general comprehensive method to investigate a new motorcycle model impact under several perspectives as: design, ergonomic, engine chassis matching, handling, dynamic performance, usage loads. The result is a user friendly tool allowing a time saving by a digital mock up prototyping. Man machine interface is the most important aspect, based on few assumptions:

- Driving style changes in time while man can assimilate and accommodate;
- A simple feedback strategy guarantees equilibrium but not skills improving: here a feed forward strategy is required;
- Comfort feeling influences feed forward process.

References

Barone S., Lo Iacono G. and Pampinella S. (2010). Progettazione emozionale statistica: esempio di applicazione a moto di media cilindrata. ATA – Ingegneria dell'Autoveicolo, 63(7/8).

Barone S., Lo Iacono G. (2011). Robust dynamic comfort modelling for motorcycle riding. Submitted.

Bencini M. (1956). Dinamica del veicolo, Milano: Tamburini.

Box, G.E.P., Hunter, H., Hunter, G. (1978). Statistics for Experimenters. John Wiley & Sons, New York.

Cocco G. (2001). Dinamica e tecnica della motocicletta, Vimodrone: Giorgio Nada Editore.

Cossalter V. (2002). Motorcycle dynamics, Padova: Lulu.

Cossalter V. (2001). Cinematica e dinamica della motocicletta, Padova: Edizioni Progetto.

Chakhunashvili A., Barone S., Johansson P., Bergman B. (2009). "Robust product development using variation mode and effect analysis." In: Exploring unreliability and its countermeasures. Ed. Bergman, Lennart, de Maré, Svensson. John Wiley & sons.

Genta G. (1997) Motor Vehicle Dinamics – Modelling and Simulation, Singapore: World Scientific Publishing Co.Pte Ltd.

Lo Iacono G. Barone S. (2011). New frontiers of robust design to human variation. Application to motorcycle concept. Submitted.

Montgomery, D.C. (2001). Design and Analysis of Experiments. Wiley

Motta R. and Bordone M. (2003). Biomechanics of tendons in physiological and pathological conditions (in Italian), unpublished bachelor thesis, University of Pavia, Italy.

Porter M. and Gyi D.E. (1998). ‘Exploring the optimum posture for driver comfort’, International Journal of Vehicle Design, 19(3), 255–266.

Chapter 6

Comfort-structural analysis in product development

Optimization of a motorcycle frame

Industrial Engineering Dept (DICGIM - UNIPA)
UNIVERSITÀ DEGLI STUDI DI PALERMO

Comfort-structural analysis in product development

Optimization of a motorcycle frame

G. Lo Iacono, C.Liperni, G. Marannano, G. Virzì Mariotti

Abstract

This work steps from a bachelor thesis, joining the results of a study about the dynamic loads to evaluate the comfort loss in the motorcycle during the usage, with the potentiality of a modern FEM software: the goal is to develop a new methodology for structural optimization of motorcycle's frame. In the most of cases the success of the structural optimization is linked with a two factors combination: the software and the strength of the engineer to condition the mathematical problem, defining parameters domain and technological constraints. In this case the weight of the simulation in the conditioning problem is determined by the human machine interaction in a very specific working situation, rather than a general one. We focused on a good alternative to the traditional load hypothesis linked to historical data or instrumental measurements. Consistent with the tendency to hyper-specialization, the machine has to fit the final user, with his anthropometric characteristics and a neutral riding style, in order to save calculation time, physical driving test and finally metal-weight saving, and money.

Keywords: motorcycle modeling, dynamic simulation, topology persistence, frame structural optimization

1. Introduction

As well known the product development needs strategic placement investigation as well as practical issues solving. The “emotional component” in sales is one of the most important topics in strategic planning (Barone, Lo Iacono, Pampinella, 2010). Afterwords a physical calibration for real usage of the product is required, being related to conceptual project by focusing on a target population and its way of using it. The most stressed component of the motorcycle is the frame, the load changing type case by case with the rider’s characteristics and the riding style. Then the engine and the brakes are also very important items. Here a very accurate investigation on the real loads of a very specific usage has been conducted, in order to get a structural optimization of the frame, a very important issue for the implications in design and in dynamical performances.

To realize this project a 1977’s KTM Penton 250 frame has been investigated, by building a 2010 Solidworks virtual model. It is a solid model with geometric input parameters, useful to apply a structural optimization using the FEM software Ansys 13 Workbench, to get a weight reduction within keeping the same structural strengths. The dynamic investigation has been performed using a dedicated Visual Basic software, “Progetto Motocicletta”, written to detect the loads exchanged by rider and motorcycle in usage, and coming from the interface between road and wheels, while an optimal trajectory is imposed

Since the motorcycle model is obsolete, it is understandable to get good results in weight reduction. Nevertheless the experience is very important for didactical scopes, as well as a solid modellation has been done starting from the physical relief, because of the lack of CAD or paper drawings: a good chance to understand the structural working way, thanks to the real frame we had for the measurements, given from the firm “Doctor Engine” by Mr. Gianluca Grilletto

2. Modeling

Dimension procedure

1977’s KTM Penton 250 frame is a steel pipes welding assembly, with double-cradle scheme and a sheet metal backbone, studied to get stiffness as well as lightness. The frame measures have been detected by a high resolution photographic relief. Seventeen high contrast markers have been applied on some key points of the frame, in order to get an easy way to localize and dimension them. In this phase we minimized the error sources, the most of them related to distortion and prospectic deformation. To get as much parallelism as possible, the film plane, was kept parallel to the sagittal plane of the item by using a bubble level to dimension and correct the slopes of the planes where the frame and the camera were put.

Moreover, to reduce distortion, a fine tuning on the focal length has been done. The focal length, defined as the distance between the optical center of the lens and the focal plane, is proportional to the zoom level. In these conditions it is possible to get a lower distortion searching a flattening of perspective by maximizing both the relief distance and the zoom level. In order to verify little distortions and mainly to get a dimensional reference for the final picture, we put also dimensional specimens near the frame, for horizontal and vertical directions. The final reference picture has been imported inside an excel file, where is possible overlapping it with a scatter plot. Seventeen waypoints corresponding to the markers have been localized on the plot with XY coordinates by using the cursor. Once reduced the distortion errors of the image plane as imported picture by using the dimensional specimens as scale factors, the waypoints have been used to determine the positions of the key points, projected on the image plane, in a relative reference system of the frame, having a conventional origin (see figure 1).

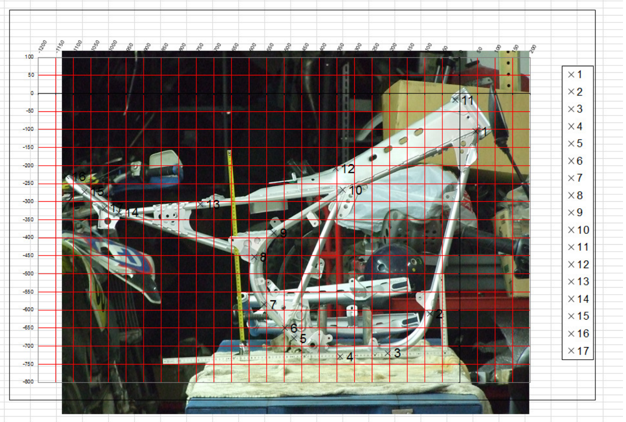
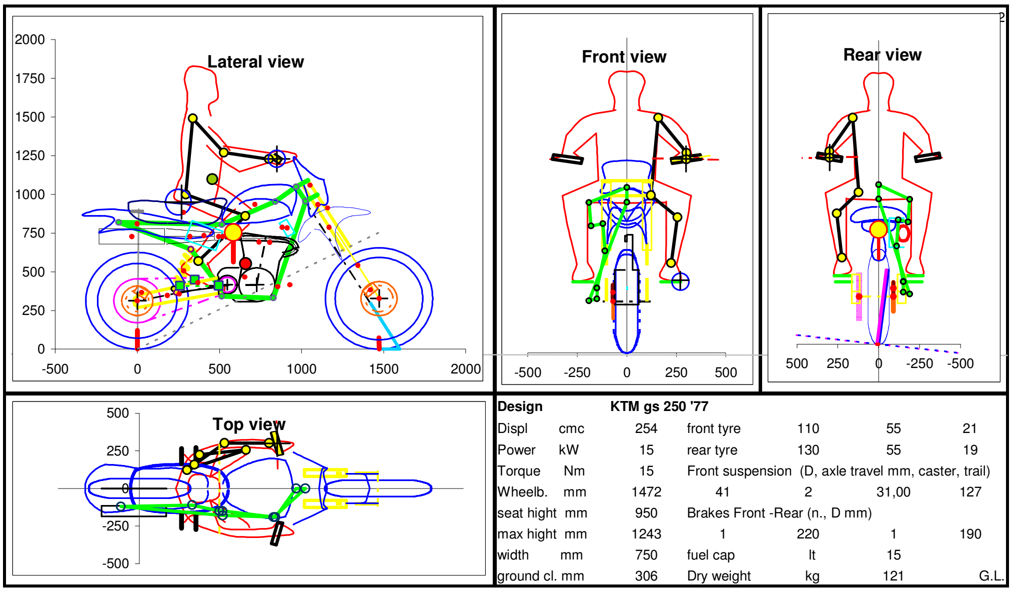


Figure 1. Overlapping waypoints scatter plot with photographic relief

Using a laser measurement, we detected the distances between the markers and a reference plane parallel to the sagittal plane of the frame. These dimensions, originally referred to the extrados of the frame pipes, have been reported to the axis, by adding the external radius of the pipes, measured with a ventesimale gauge. With this procedure we generated a 3D array, which was the starting point to generate the solid model of the frame. Some downloaded pictures helped also us to redraw the entire motorcycle digital model with the software "Progetto Motocicletta", based on modeling the overall lines of all the elements of the final general assembly, by using parametric curves (see figure 2).



Design		**KTM gs 250 '77**				
Displ	cmc	254	front tyre	110	55	21
Power	kW	15	rear tyre	130	55	19
Torque	Nm	15	Front suspension (D, axle travel mm, caster, trail)			
Wheelb.	mm	1472	41	2	31,00	127
seat hight	mm	950	Brakes Front -Rear (n., D mm)			
max hight	mm	1243	1	220	1	190
width	mm	750	fuel cap	lt	15	
ground cl.	mm	306	Dry weight	kg	121	G.L.

Figure 2. Motorcycle digital model

Creating the parametric solid model

The software utilized for the solid model generation is SolidWorks 2010. Using a three-dimensional sketch function it is possible to insert manually the coordinates of the key points, got by the relief procedure above explained (see fig 3).

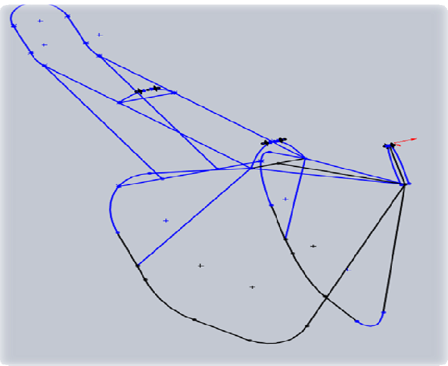


Figure 3. Perspective view of the frame skeleton

A set of parameters has been defined in this phase, by using dynamic dimensions: they are very useful input whose tuning allows a quick refresh of the solid model while the structural optimization phase is on. For the solid structure generation a welding function has been used: it follows a sweep spatial 3D path for a chosen profile. Three welding profiles have been drawn for caster, and the two different pipes sections (double-cradle and seat support): the parameters were in this case the internal and external diameters of the pipe sections.

The organization of the priority class allows to identify, among the various crossing geometries, the boundaries ones and those to be trimmed. In this way it is possible to identify, as much realistically as possible, the real constructive technology allowing to differentiate a bent joint from a welded one. Figure 4 shows how it is possible to respect the original technology with the priority class in the joint between two different size pipes.

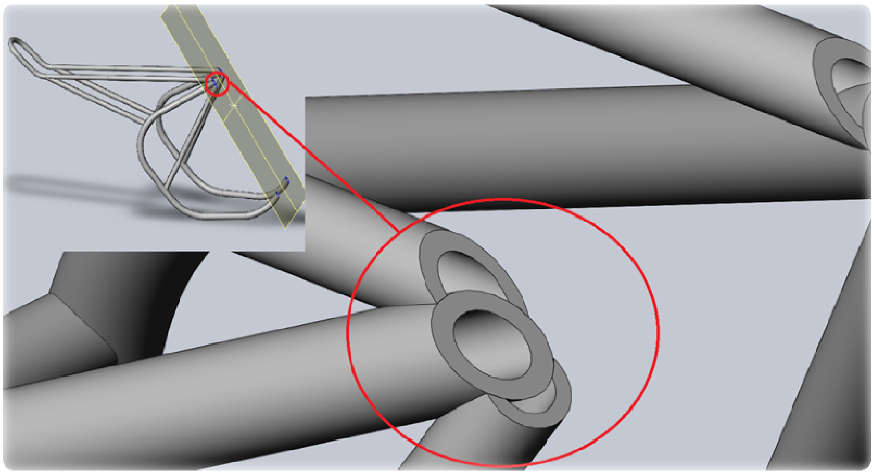


Figure 4. Cutting priority

In the generation of the sheet metal backbone, four different surfaces have been used as shell elements, with a command allowing the extrusion of both open and closed boundaries. It is possible to generate the solid sheet metal giving a thickness to the surfaces.

Finally the engine supports and the rear suspension supports have been generated by extrusions, and the caster hole by digging.

By tuning the optimization parameters has been possible to gather other possible configurations, among whom there was the optimal one, depending on the target performance.

Topology persistence concept

The topology is one of the most important areas of modern mathematics. It is the study of qualitative properties of certain objects, figures and shapes, which do not change after deformations involving stretching, but no tearing or gluing: in other words topology is the study of continuity and connectivity. The utilized software applies the structural optimization tuning simple numeric parameters, refreshing the geometry and then analyzing it with a FEM technique. This operation has to be reiterated enough times to allow creating a sort of response surface where to search combinations of input parameters useful to fit the target. The persistence of the topology, which is the feature of FEM software of identifying some geometries and priority classes, is an indispensable value-added, a fundamental constraint in the analysis of different geometrical configurations, sometimes guaranteed by the software with a manual identification of particular areas of the solid model.

The solid approach, new frontier of design, definitely needs this feature, which has been in the past its major limitation. To guarantee the persistence, without limiting the power of the analysis, the modern software utilize a common interface with the CAD software, in order to identify and mark the geometries as persistent through different configurations.

In the analyzed frame seven surfaces have been marked as application areas of loads or constraints: four engine supports, the caster and the rear suspension supports.

3. Motorcycle dynamics

Understanding motorcycle dynamics allows to identify in a quantitative way the loads stressing a motorcycle frame in a specific usage, very important step for the success of an optimization procedure. During a radical design, building prototypes for experimental measurements of the working strains is extremely expensive. Moreover reproducibility of experimental sessions would be affected by prototyping variation.

Since the machine testing requires an interface with the rider, we can find several other reasons to avoid the experimental way, concerning the repeatability concept: despite his skills, the rider is not able to guarantee a maneuver (with instruments) always done in the same way.

The "feeling" concept deserves a particular attention. It is hardly detectable from a simulation output, despite some recent studies show a significant effort in this direction (Barone & Lo Iacono, 2011). Nevertheless all the subjective judgments have no scientific validity, because the tests they come from, are always conditioned by specific driving styles and personal skills, despite the riders are professionals.

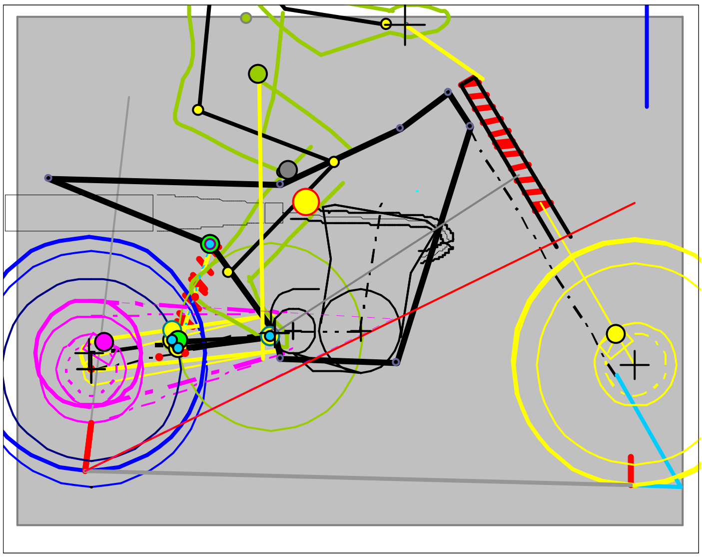


Figure 5. Digital model for dynamic simulation

The dynamic simulation are instead able to show in an objective way the motorcycle behavior, and allow an easy reading of many output parameters.

In order to identify the loads stressing the frame we studied, we utilized a computational method simulating the dynamic behavior of the vehicle along a specific imposed path. The software starts from several inputs regarding all the geometrical dimensions, but needs also information about the frame material, stiffness and damping coefficient for suspensions, the torque characteristic of the engine, the gear ratios and tires specifications as from the tables provided by the builder and the official literature about the motorcycle. The figure 2 shows the input screen for 1977's KTM Penton 250. Also the imposed 3D trajectory is an input, a joint of several parametric curves, together with friction coefficient for tires-asphalt contact and rider's anthropometric data.

The simulation is done with a human manikin representing the 50th percentile of the reference population (Italy). This input is very important for the computation of dynamic loads output of the human machine interaction simulation, because it seconds the best possible performance according to the boundaries constraints, which are the imposed trajectory, the grip level, the weight distribution of the binomial rider-machine. In this way the output of the computation are the loads that the rider has to equilibrate with handlebar and lateral weight movement to permit the dynamic performance. If these loads are sustainable by the rider, actually a neutral driving style is generated. A neutral style is preferred because, being not influenced by any predisposition of the rider, and together with the robust comfort modeling done using a percentile weighed sample, surrogating an entire population (Barone & Lo Iacono, 2011), it represents the best solution for the following optimization, since it determines a load history not affected by the noise factors involved in this field: the anthropometric dimension and the rider driving style.

The data regarding the inertias, needed for the dynamic analysis, can be introduced as input or easily computed starting from other inputs as geometry and mass properties of constituent materials.

Dynamic simulation

The motorcycle is analyzed both cinematically, with the analysis of the motion state coming out by matching between the tridimensional path and the engine features, compatibly with the dynamic ones, and dynamically with the analysis of all the internal and external forces over time. It is required setting the characteristics of the trajectory step by step, with a discrete array containing longitudinal and cross slope, and curvature radius. Other needed inputs are the gear ratios, the engine torque VS rotational engine speed diagram, the braking torques.

The simulation has been done in this case along part of the path shown on the figure 6, with one right and one left curve.

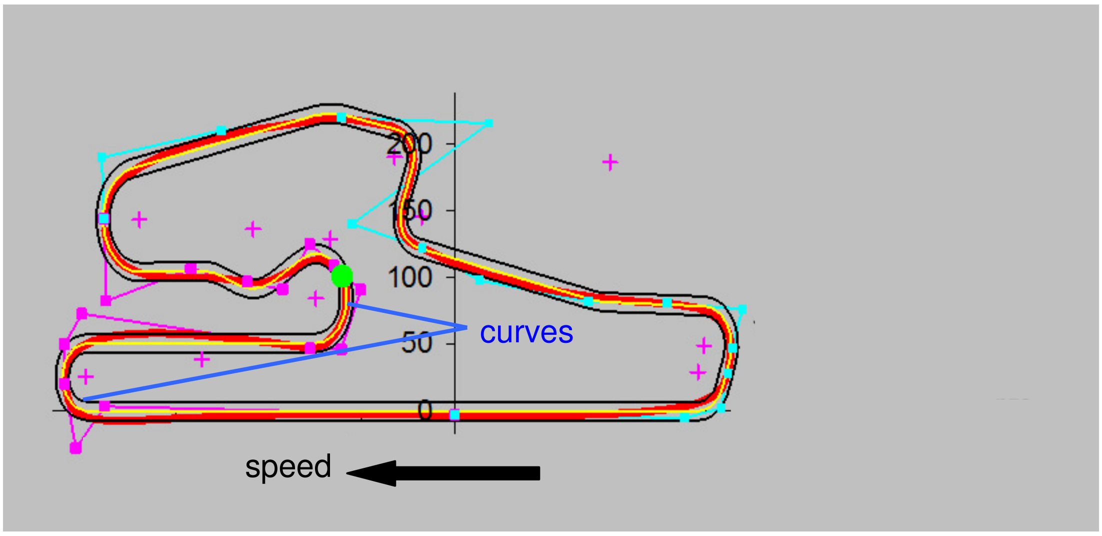


Figure 6. Circuit for dynamic simulation

The vehicle starts with zero speed, and when an almost 100 km/h speed is reached, a sudden deceleration occur due to the braking torque application on the front wheel. The motorcycle follows the first right turn and after a second rectilinear there is the left curve. The Visual Basic dedicated software “Progetto Motocicletta”, returns the speed, roll, braking diagrams. The reference system is united to the motorcycle, with x axis as longitudinal, while a cross plane having the normal reference N of the road, including the cross slope point by point, is utilized to calculate the grip forces equilibrium in lateral motion. During the performance the rider can tune the value of the offset with the motorcycle sagittal plane, allowing the system, with a step by step feedback system, to achieve a rolling speed around a target one, which is calculated in order to keep the rolling equilibrium in riding. To let this dynamic functioning, also equilibrium forces are needed on the handlebar, while also lateral derive forces come up in the computation, when inertias overcome the top friction forces, which the road and the tires can exchange. When these forces are discordant, a yaw motion starts. To avoid derive forces an engine control cuts the torque. The pitch motion control is not implemented, because it doesn’t affect the issues this software was created for.

The gyroscopic effects are computed separately, on front and rear suspensions. They are transmitted to the entire motorcycle. In particular on the front suspension the equilibrium has to take into account the constraints of the handlebar bearing, which allows torque transmission only through axis which are orthogonal to the caster one. This detail makes motorcycles very special machines.

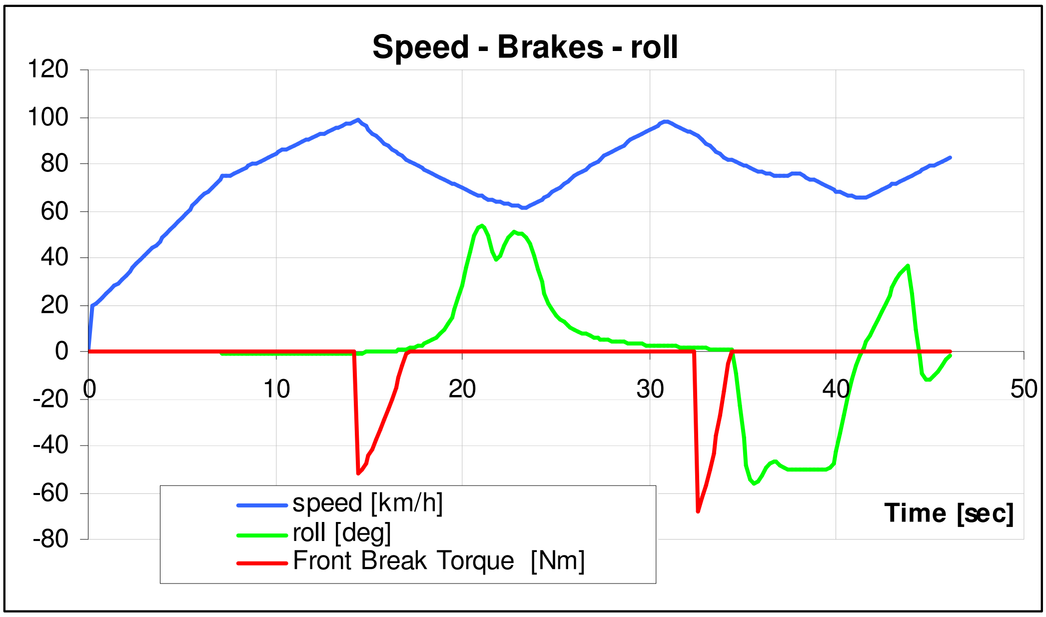


Figure 7. Speed, braking torque and roll diagrams during simulation

The graph in figure 7 shows two acceleration phases where the speed reaches almost 100 km/h value. At these times the application of a braking torque makes possible a deceleration from 100 to 60 km/h. The roll angle diagram shows how the braking is linked to the corner entry, which shows up with an upgrade to the 53 deg, value corresponding to the central part of the curve. In the following seconds the roll come back almost to zero during the rectilinear between the two curves, where there is a new significative acceleration. The left curve shows the same attitude of the right one but with a negative roll, as understandable.

Corresponding to the different phases of the circuit, there are associated the normal reactions on front and rear wheels. The knowledge of the suspensions geometries allows to detect then the components transmitted to the frame. In the front suspension there is a component alongside the caster axis, and one orthogonal. In the rear suspension the global force alongside the axis of the dampers has components both in the upper axis, linking the dampers with the frame, and in the main axis of the swing arm.

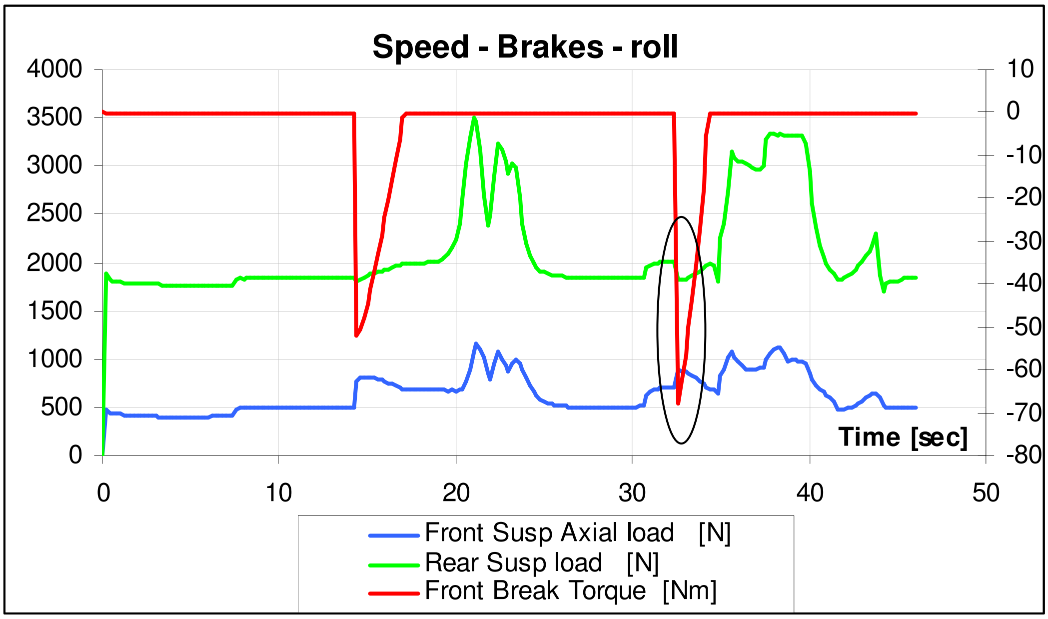


Figure 8. Braking torque and suspension forces diagrams during simulation

Figure 8 shows the diagrams of the loads of front and rear suspensions. The braking torque time history makes easy understanding this kind of diagrams: during the braking phase is clear the occurrence of a load transfer between front and rear suspensions, with an increment in the front suspension, especially in the second curve, near the maximum absolute value of braking torque.

In the following time the stop of the braking action and the curve riding of the motorcycle determine a new distribution of forces, which at the beginning have values similar to the ones during the rectilinear part, but then they arise new higher levels, both in the front and in the rear suspensions, because of the showing up of the inertial forces and consequently of upper loads on the interface between asphalt and tires, according to lateral equilibrium.

The cutting force on the front fork shows a sudden rising of the value, during the braking, to the maximum of 806 N.

4. Structural optimization

Preliminary structural analysis

Before the real optimization, a structural analysis has been done in order to detect the worse case in the existing item, by stressing the structure with the load history we had got from the dynamic analysis. The chosen indicator was Von Mises stress, investigated with FEM method. It is a very important step, conditioning the success of the following optimization.

In this phase a first conditioning of the problem takes place, with the identification of the best solution. In one hand the more element are in the mesh the best, but the number is limited by the computational cost in the modeling equations solving.

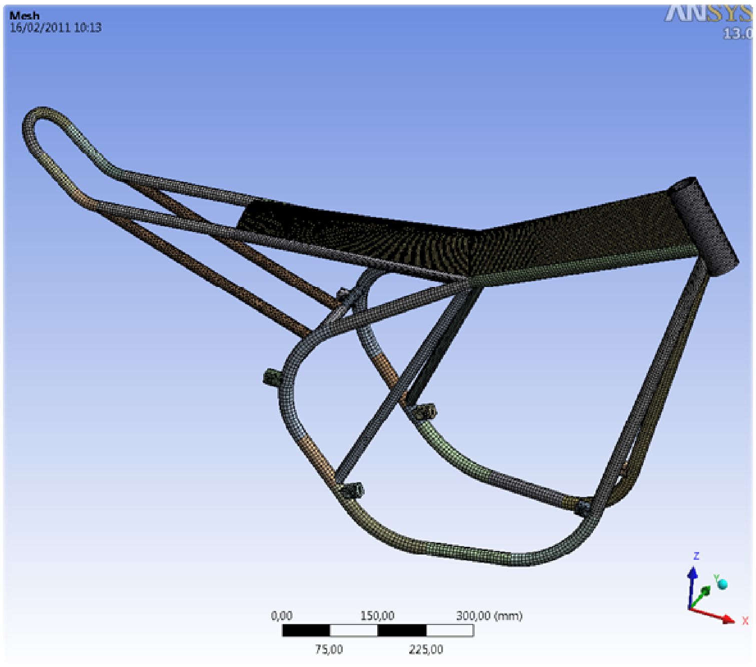


Figure 9. Model discretization

We utilized the multibody model, built with a discrete number of separated solid bodies. They interact between by exchanging loads and strains, within specific sets of constraints. They are contact elements, generating forces in order to avoid compenetration and so working in the right way, transmitting the essential loads.

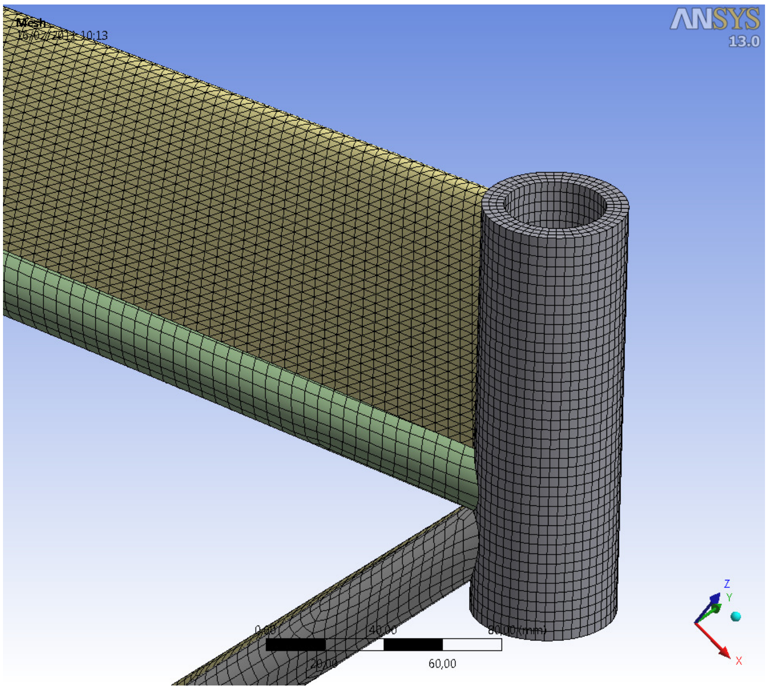


Figure 10. Mesh caster particular

The load history comes out from the dynamic analysis providing the time table of the forces charging the frame in the joints for front and rear suspensions. The finite element method software allows to insert these load conditions by using a particular interface with the Visual Basic software "Progetto Motocicletta".

The software interface provides external loads only through wheels and suspensions, whom normally are considered as constraints: so the structure should be fleeting, unless new artificial constraints are set as boundary conditions. For this reason some cylindrical supports in the engine joints have been created as constraints. This solution comes out by evaluating the engine as the heaviest item of the motorcycle, capable of the highest inertial reactions to any motion state changing. By the way all the external and inertial loads are in equilibrium over time, so the reactions in these artificial constraints compensate only the computational errors in dynamic simulation.

The analysis done returns a top stress at time 16,4 sec when the top cutting force on front suspension reaches the top level.

At this time the loads on the frame are:

F_b_front= 806,22 N

F_s_ front = 452,90 N

F_s_rear= 837,27 N

The most stressed point is in the joint between the caster and the backbone, since the front suspension cutting load is the origin of the top stress.

Moreover the software evaluated also the weight of the frame returning the value before measured, of 16 kg.

Choosing the optimization algorithm

The structural optimization phase has the scope of modifying the frame in an appropriate way, without compromising its strengths, and in order to reduce as much as possible the mass. Here a parametric optimization has been adopted, using discrete variables, some defined by the user and some chosen in a predefined values set inside a validity range, with both technologic and design constraints.

Inside this design space seven dimensions, in order to modify the model geometry, have been defined. Operating inside the design space, the structural optimization can search the combination allowing to get the design target.

Independent variables input set.

-P1 Frame width under the seat

-P2 Frame width on caster

-P3 Backbone spline command point

-P4 Backbone spline command point

-P5 Internal diameter section 1

-P6 Internal diameter section 1

-P7 Backbone sheet metal thickness

Mass and equivalent Von Mises stress has been defined as dependent variables.

In order to predict the response of the structure inside the design space, a specified number of analysis is required, changing the independent variables input set.

The number of points where evaluate the response is:

$$(1+2N+2^{(N-f)})\prod_{i=0}^{M} v_i \tag{1.1}$$

Where:

N Number of continuous parameters

F Entire number associated to N

M Number of discrete parameters

V_i Allowable values for generic parameter i

Here five continuous N parameters have been defined: the software associates F=1. Also there are two discrete M parameters, and for each we indicated three admissible values V.

The software then creates a design space with a 243 combinations dimension.

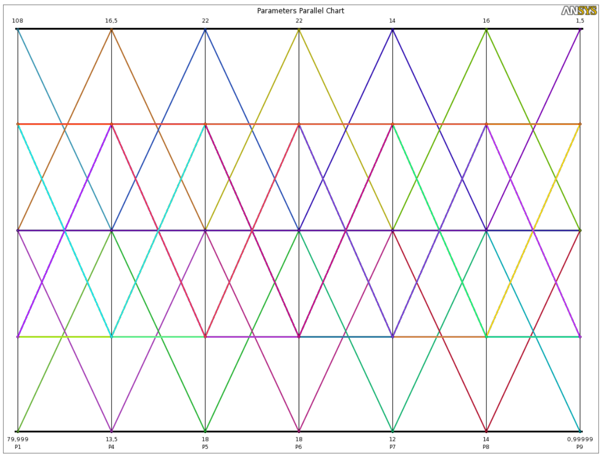


Figure 11. Parameters parallel chart

Fig 11 shows the scheme of the design space as output from Ansys, named *parameters parallel chart*, where each parameter has four levels on y axis as before set with the admissibility range. Each of the 243 combinations has a path identified with a single color, identifying each parameter value by crossing one level line out of four.

Despite the big number of combinations to analyze, and the complexity of the problem, the required computational time was only 43 hours, given the high conditioning level of the problem. The top Von Mises stress value should be lower than 62 Mpa, corresponding to the maximum stress calculated in the original frame under the same load conditions.

The described procedure returns a geometric parameters set satisfying the required characteristics: mass reduction with same structural stress level, and same strengths.

In the table below the values of the constructive parameters in the optimized frame are reported.

Tab. 1 Parameters optimization

Parameter	Original value [mm]	Optimized value [mm]
P1	104	90,2
P2	15	13,5
P3	20	18
P4	20	18
P5	12	13
P6	14	15
P7	3	2

In order to validate the procedure a dimensional refresh with the optimal parameter values has been done, with a new structural analysis: the new frame design has now a 14,7 kg mass out of the original frame 16 kg mass. A 8,1 % mass reduction has been achieved.

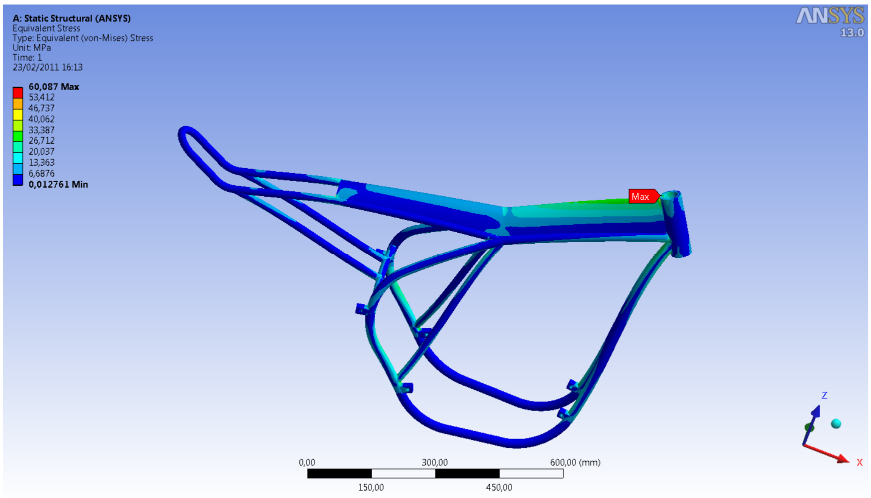


Figure 12: Von Mises stresses in optimized frame

Moreover matching the stress maps from the two different frames, is possible to appreciate a more homogeneous distribution of the Von Mises stresses along all the backbone extension.

5. Conclusions

The objective of this activity has been to join the results of a dynamic simulation for motorcycles, created for rider comfort loss evaluation in usage, with the potentiality offered by a modern FEM software. Starting from an existing motorcycle frame, 1977's KTM Penton 250 frame, 16 kg mass, has been possible generating a parametric model capable of reproducing with an high reliability the original constructive technology. The dynamic simulation is conducted using a human manikin, reproducing human shapes of the 50th percentile of a reference riders population, in order to detect the loads coming out from human machine interaction, when a "neutral riding style" is adopted. Decisive were the software technology and the skills of the designer to condition the mathematical problem, while the starting point were not general hypothesis about the load history, but the human-machine interaction. This is the value-added we want to highlight now: a step towards an homocentric perspective rather than the traditional load histories based on historical or instrumental data. The simulation in this case is searching for a comfort level which the final user can accept.

The described procedure shows its flexibility: for one hand it can be utilized for improving the existing motorcycle frames, but also it can be implemented for new model designs, thanks to the important feature of conducting dynamic analysis to detect the stress levels, with the CAD usage limited to the frame parametric model for the structural optimization, since it is possible working with virtual digital models entirely built and dynamically evaluated inside the software "Progetto Motocicletta". Here a frame optimization has been achieved, with a 8,1 % mass reduction within same structural stresses levels. This reduction has to be considered generated inside very specific usage conditions, which can be extended, but basically always studied under the perspective of a robustness to noise factors as driving style and anthropometric variability.

References

Barone S., Lo Iacono G. and Pampinella S. (2010). Progettazione emozionale statistica: esempio di applicazione a moto di media cilindrata. ATA – Ingegneria dell'Autoveicolo, 63(7/8).

Barone S., Lo Iacono G. (2011). Robust dynamic comfort modelling for motorcycle riding. Submitted.

Bencini M. (1956). Dinamica del veicolo, Milano: Tamburini.

Cossalter V. (2002). Motorcycle dynamics, Padova: Lulu.

Cossalter V. (2001). Cinematica e dinamica della motocicletta, Padova: Edizioni Progetto.

Cocco G. (2001). Dinamica e tecnica della motocicletta, Vimodrone: Giorgio Nada Editore.

Genta G. (1997) Motor Vehicle Dinamics – Modelling and Simulation, Singapore: World Scientific Publishing Co.Pte Ltd.

Lo Iacono G. Barone S. (2011). New frontiers of robust design to human variation. Application to motorcycle concept. Submitted.

Polucci G., Guerra G. (2003). Dimensionamento di un Telaio di Motocicletta: Modello di simulazione e risultati di calcolo. Moto Tecnica, 17 – 8.

Polucci G., Guerra G. (2003). Dimensionamento di un Telaio di Motocicletta: Identificazione dei Carichi. Moto Tecnica, 17 – 10.

Juvinall R., Marshek K. (2001). Fondamenti della progettazione dei componenti delle macchine, Pisa: Edizioni ETS.

ANSYS Realase 12 Documentation. ANSYS, Inc, 2004.

Sito internet www.ansys.com

Sito internet www.mece.ualberta.ca/tutorials/ansys

Sito internet www.ozeninc.com/default.asp?ii=84

Appendix 1

Attacking a problem of low capability in final machining for an aircraft engine component at Volvo Aero Corporation

Extracted section from chapter 6 in Barone S., Lo Franco E. (2012). Statistical and Managerial Techniques for Six Sigma Methodology. Wiley

ATTACKING A PROBLEM OF LOW CAPABILITY IN FINAL MACHINING FOR AN AIRCRAFT ENGINE COMPONENT AT VAC - VOLVO AERO CORPORATION.

Project purpose: to find main sources of variation in the manufacturing process of a turbine exhaust case – TEC, in order to increase capability in final profile tolerance requirements and assure optimal conditions before starting final machining phase.

Organization: VOLVO AERO CORPORATION

Duration of the project: Five months (2011)

Black Belt Candidates Team:

Johan Lööf, Ph.D, Volvo Aero Corporation

Christoffer Löfström – master student; Giovanni Lo Iacono – PhD student.

Phases carried out and implemented tools: Define (project charter, Gantt chart, “Y” and “y” definitions, Ishikawa diagram, SIPOC) - Measure (brainstorming, observations, pictures, Ishikawa diagram, geometric optical measurements) – Analyse (correlation, regression, normal probability plot, capability analyses, control charts).

1. Presentation of Volvo Aero Corporation:

Volvo Aero is a company located in Trollhättan, Sweden that develops and manufactures components for commercial and military aircraft engines and aero derivates gas turbines. In this area, we have specialized in complex structures and rotating parts. We have market-leading capabilities in the development and production of rocket engine turbines and exhaust nozzles.

The main challenges for the flight industry today are to reduce the emissions CO2. The lighter an aircraft engine is, the less fuel it consumes for any given flight. That's why we focus on developing lightweight solutions for aircraft engine structures and rotors. Our optimized fabrication of fan/compressor structures and turbine structures, realized through our advanced computer weld modeling, makes these structures lighter than conventional single-piece castings. Moreover, we have also developed our fabrication processes to high levels of automation in order to reduce costs, improve robustness, and optimize fabrication concepts, especially when the manual assembly is not feasible.

2. Project background:

In the production today it is hard to reach capability goals in the final profile tolerance requirements on a structural component. This component consists of a number of parts that are welded together in a number of steps and then machined to its final form. The machining process consists to a big part of removing (e.g. shaving off) excess material to make the whole component meet tolerance requirements and to provide surface treatments needed before delivery. Today there are problems with variation of geometric deviations in different steps of the manufacturing process which leads to long lead times in the final machining phase to be able to meet the customer requirements of maximum nominal deviations in the finished products. This may in worst case even lead to scrap of a whole component.

3. Define phase:

The manufacturing process consists of a large series of sequential operational steps that can be grouped together as operations with measuring steps in between. A number of incoming parts are measured and then placed into a fixture and tack-welded together. Another measurement is then carried out to find out if the parts still are in their thought positions after the welding. If they are in their correct positions the parts are permanently welded together, if not their positions are corrected and a new measurement performed until satisfactory results are achieved before moving on to the next step in the process. The operation steps contain of adding of material with different welding techniques, measuring, possibly aligning, and cleaning and preparing surfaces for the next material to be added. At the end of the process the whole assembly is x-rayed to see that welds are meeting requirement standards and if necessary weld-repaired, before the assembly is heat-treated and sent off to final machining. This is where the process stops and the final machining group take over as internal customer.

The big Y´s are defined in the measurement operation after the heat treatment. In this project focus have been set on four critical areas on the product that has to be in statistical control before entering the final machining phase. These four areas are measured in each of the seven measurement steps.

As input into the process there are the incoming parts supplied by an internal supplier at VAC, the welding functions supplied by Production and the measuring and controlling by the Control and Measure function. The numerical requirements on the inputs are geometrical tolerance requirements on the incoming parts. The measurement requirements are fulfilled in view of accuracy and reliability. When it comes to the input from the operators' performance we have marked them as grey in the SIPOC (see Figure 1) since they are outside the limitations in the project, but still included them in the graphics for comprehensiveness. The outputs of the process are the weld assembly with the numerical requirements of meeting geometrical profile tolerances fulfilled.

Other outcomes from the define phase are a project charter (Figure 2), a Gantt schedule and a first level Ishikawa diagram based on brainstorming that will be more detailed and further sorted out after coming meetings with the final machining manager and the quality managers of the process.

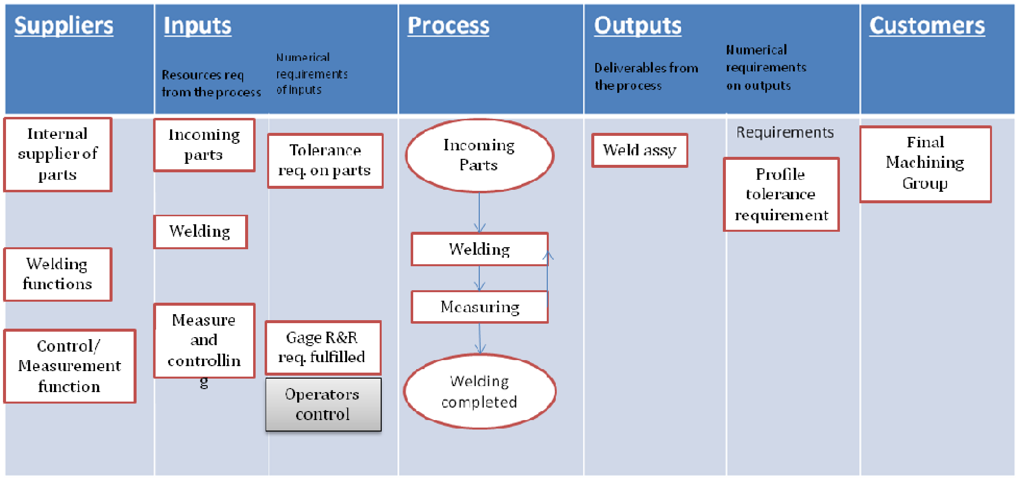


Figure 1. SIPOC diagram

Company (organization)	**Volvo Aero**	**Unit/Department**	**7163/DfR**
Industrial participant (Black Belt candidate)	**Johan Lööf**	**Telephone/e-mail**	**Johan.loof@volvo.com**
Sponsor & process owner (Manager Production)	**(masked data)**	**Site or location**	**VAC-THN**
Project Start Date	**20110201**	**Project completion Date**	**20110524**
Expected impact level		**Expected financial impact (savings/revenues)**	**Decreased lead time for final machining.**

<table>
<tr><td>Project summary</td><td>A short description of the project</td><td colspan="4">Problems with low capabilities in the final machining process causing problems in the ramp up phase of structural component manufacturing. In order to achieve a better outcome of the process, we need to investigate how big the geometric deviations are and where they occur before going into the final machining process. The final goal of this project is to find main root causes to the geometric deviations such that we can make improvements in order to assure optimal conditions before starting final machining.</td></tr>
<tr><td>Impacted process</td><td>The specific processes involved in the project</td><td colspan="4">Assembly processes of complete product starting with parts from internal supplier. This includes fixturing, welding, heat treatment and inspection (NDT=None Destructive Testing).</td></tr>
<tr><td>Benefit to customers</td><td>Define internal and external customers (most critical) and their requirements</td><td colspan="4">Production Trollhättan. To reach acceptable capability of identified quality problem.</td></tr>
<tr><td>Benefit to the business</td><td>Describe the expected improvement in business performance</td><td colspan="4">Enhances both in lowering of lead-time and improvement in quality cost.</td></tr>
<tr><td>Project delimitations</td><td>What will be excluded from the project</td><td colspan="4">The project will concentrate on a specific area on the complete product in order to make it possible to get a result within this course.</td></tr>
<tr><td>Required support</td><td>Support in terms of resources (human and financial) required for the project</td><td colspan="4">Travel costs (students)</td></tr>
<tr><td>Other people involved</td><td>List technical experts and other people who will be part of the team</td><td colspan="4">Machining experts, Component owners, Producibility leader, Quality leader, Welding experts</td></tr>
<tr><td rowspan="2">Specific goals</td><td rowspan="2">Define the baselines, your realistic goals for the project and the best case targets for improvement.</td><td>Actual value (baseline)</td><td colspan="2">Realistic goal by project end date</td><td>Best case goal</td></tr>
<tr><td>(masked data)</td><td colspan="2">(masked data)</td><td>(masked data)</td></tr>
<tr><td>DEFINE phase completion date</td><td>2011-02-24</td><td colspan="2">MEASURE phase completion date</td><td colspan="2">2011-03-29</td></tr>
<tr><td>ANALYZE phase completion date</td><td>2011-04-21</td><td colspan="2">IMPROVE phase completion date</td><td colspan="2">2011-05-05</td></tr>
<tr><td>CONTROL phase completion date</td><td>2011-05-20</td><td colspan="2">PROJECT results presentation date</td><td colspan="2">May 25th, 2011</td></tr>
</table>

Figure 2. Project charter

4. Measure phase:

The measurement steps are carried out by GOM (Geometric Optical Measurement) and CMM (Coordinate Measuring Machine) where data is recorded and kept in the system. While the CMM only is carried out at a few single stages, the GOM-measurements cover the whole process measuring in all stages that are considered potentially critical and are therefore our natural choice of data to focus on. GOM is a measurement system based on a camera that records hundreds of still images of an object that are being put together in the computer system into a single 3D-image of the object. The object's geometrical deviations from a reference model (the nominal values) are color coded and the image tells information on the magnitude and direction of the deviation.

The detailed Ishikawa diagram (Figure 3) constructed during this phase highlighted that the main problem of variation seems most likely to be due to the welding operations that when performed transfer a significant amount of energy in form of heat into the surrounding materials. These materials are usually of both different compositions and thickness that leads to different degrees of expansion/contractions and cooling times that results in stress building up in the material when cooling down back to room temperature. This stress causes the still not cooled material to move somewhat which in its turn leads to geometrical deviations. The variations are tried to be controlled and held as low as possible by trying different welding techniques that are more focused and concentrating the heat transfer into a much smaller area leading to lower temperatures in surrounding area and less material stress than compared with conventional welding techniques. This has reduced the effects but some movements still remain.

Then there is another difficulty that also stems out material heating. In the final machining the weld assembly arrives after the heat treatment. Here the assembly may be well within tolerance limits before the heat treatment but both thanks to built in stress since earlier weld operations and the new heat and cool cycle critical the assembly may get outside tolerance limits.

Due to our limitations we have basically two options when approaching the process. The first one is to investigate how much the incoming parts are affecting the output of the process by analyzing the geometric variations of these parts and measuring their contribution to the total process variation. The second approach is to focus on the measuring procedure and on how the parts are placed into the fixture before they are welded together.

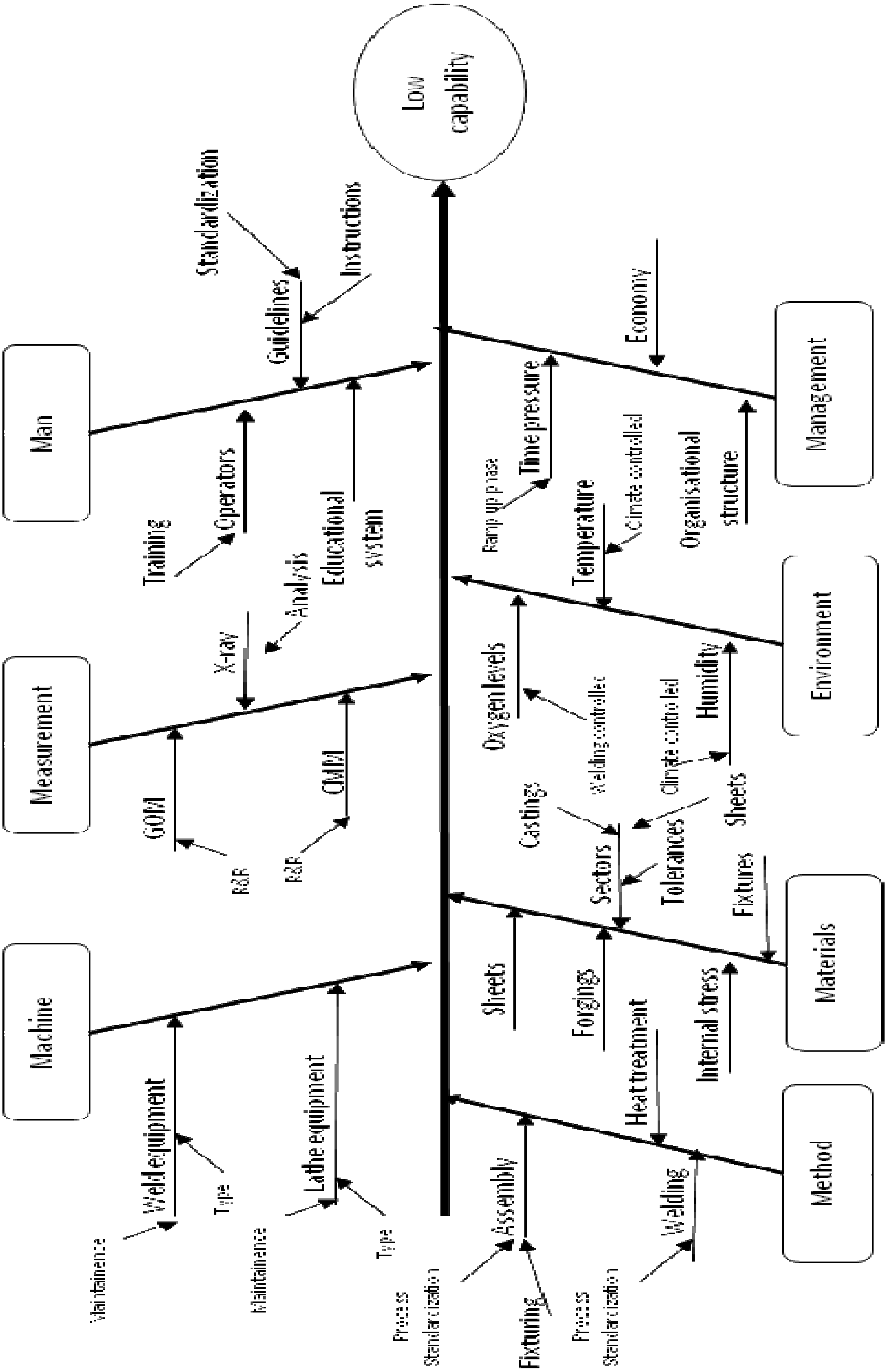


Figure 3. Ishikawa diagram

The adjustments are done manually, and specific guidelines help operators to place the parts in the correct position. Thanks to these adjustments a whole component is well fit within tolerance limits but can be slightly shifted from the nominal position that the measurement system has as reference. These shifts will be recorded and, consequently, taken into account into coming operations steps. That may cause operational procedures unnecessary or wrong.

From the process meetings there are some details of the component that have been identified as most critical to fulfill the output tolerance requirements. These details (see Figure 4), so called "bosses", are easy to identify and unlikely to deform geometrically (i.e. compared to the surrounding material). The four bosses have different functions. In the center of each boss there is a hole; if the boss is not within its tolerance limits there will not be enough material surrounding the hole to fulfill the material strength requirements.

Each boss has been divided into sixteen subareas where are located the points where GOM measurements are made (see Figure 4 and Figure 6).

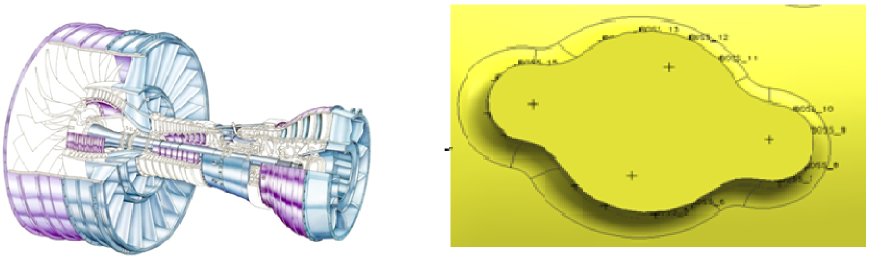


Figure 4. The aircraft engine (to the left), a boss on an aircraft component (to the right)

This type of GOM data is stored in the system as color-coded pictures that give qualitative information on the magnitude and direction of deviation from nominal values. Figure 5 shows the measured points on a boss and a color-coded GOM data picture. GOM pictures do not contain quantitative information of deviation or direction of deviation in any fixed points (except for maximum and minimum deviations, and the deviation of the point 5 on the bosses). So, data have to be ordered and measured by specialized personnel in order to analyze specific points on a boss. GOM pictures show a nominal positioned boss silhouette in black, the actual boss position silhouette is placed on top of it. The actual position silhouette holds different colors depending on the size and direction (i.e. positive or negative direction) of the deviation. On the right side of each picture there is a colored scale, the pictures concerning the same boss are then put together in series (see Figure 5).

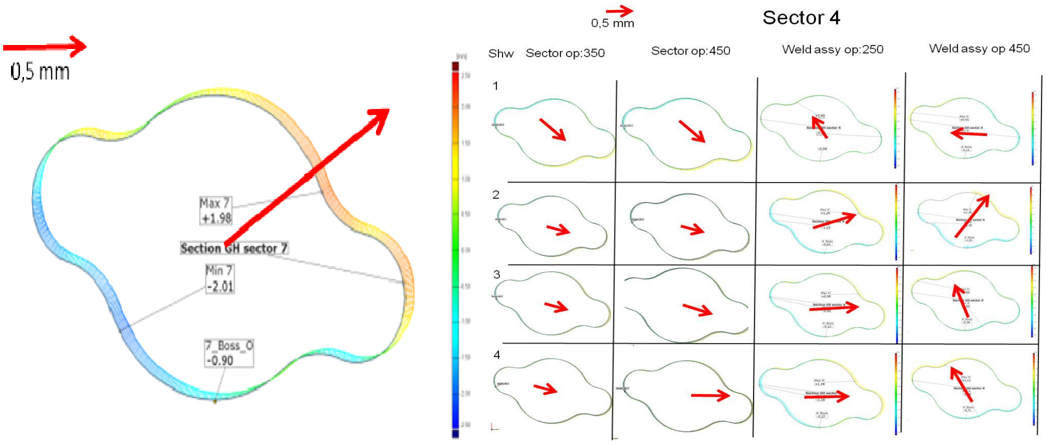


Figure 5. GOM pictures

5. Analyse phase:

Figure 5, on the right, shows how one boss moved during four different process operations on four different components. A visual analysis highlights a clear trend both in the movement direction and in the magnitude of the bosses in the sector level.

The process starts with the incoming parts. Some of this incoming parts are identical and has a boss placed on the outer surface. The first analysis consisted into measure the capability of one point on the boss in a certain direction illustrated by the arrow in Figure 6. There is a tolerance requirement on the position of the boss of ±1.5 mm (general) in that direction.

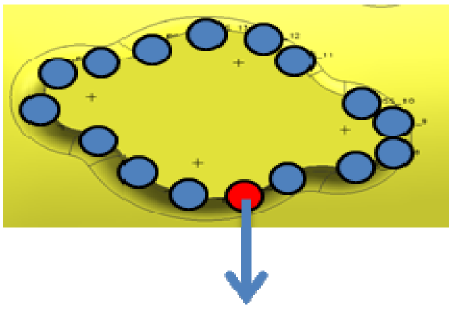


Figure 6. Critical direction of a point on the boss

In order to deepen the knowledge on the distribution of data, capability and normality analyses were performed (Figure 7): the process is normally distributed and is stable but with a drift from the nominal value and a low capability (see for example Figure 7).

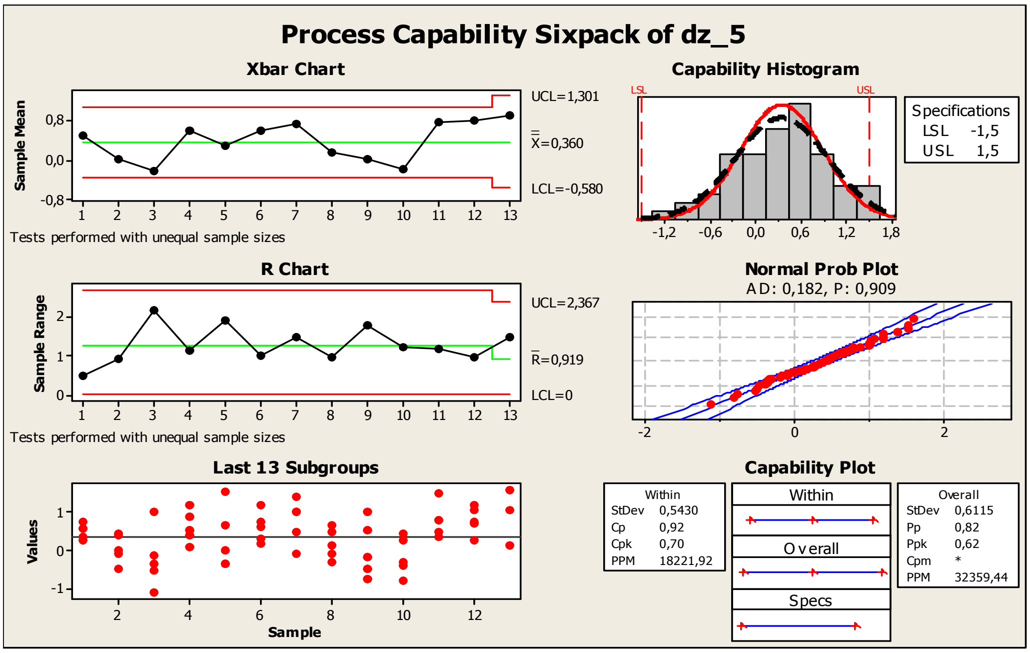


Figure 7. Capability analysis

The next step was to investigate on how the boss performs not only in the Z direction but also in the X direction by a correlation analysis. Analyses show that the bosses all rotate in the same way and the process is stable, since stochastically independent events (the related manufacturing processes) head to the same kind of performance. There is not a correlation between the maximum / minimum displacements across the series.

In Figure 8, the position of one boss can be followed through the seven different measurement operations.

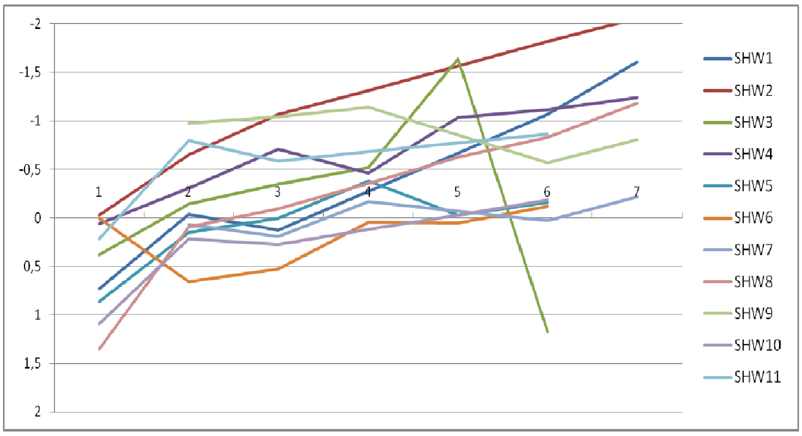


Figure 8. Seven different measurements of one boss.

After having measured the capability of the incoming parts and the outcome in the Big Y, the next step was to investigate which process contributes the most to the final variation.

There are seven different phases that affect the variation in the big Y: firstly, the position of the bosses, then the six phases allocated between the measurement operations. In order to calculate the contribution of each phase to the variation, the differences of data resulting from consecutive measurements (one in correspondence of each phase) were calculated. In Figure 9 the capabilities associated to each of the six phases are shown. In order to calculate Cpk values, a tolerance of ± 1 mm has been defined. For the boss considered, the main contributors to the variation are the processes located between "Op1" and "Op2" measurements. Certainly, also the incoming position of the boss affects the outcome significantly, since the capability value is 0,7 and the tolerance limit is ±1,5 mm.

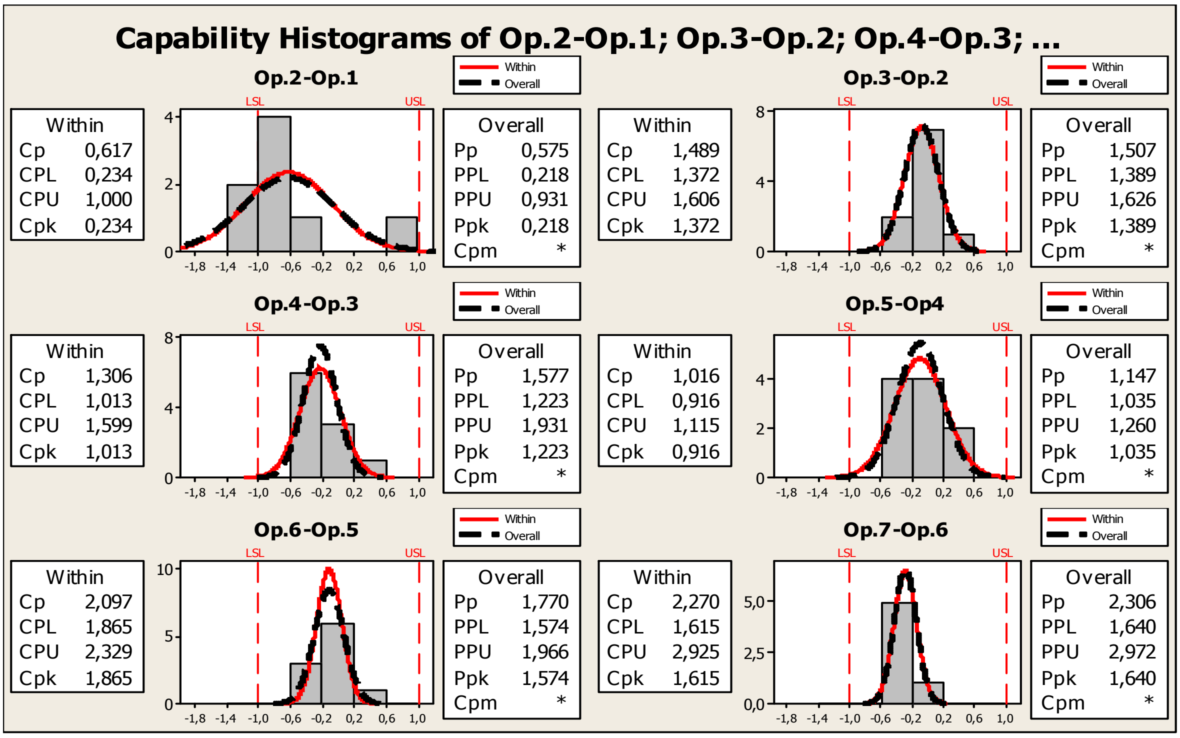


Figure 9. Capability associated to the seven process phases

6. Improve phase (ideas and intentions):

Analyses concerned only six components that exceeded the measurement stage before starting the final machining phase, so it is necessary to collect data concerning the other components in order to analyse, in a more complete way, the real situation about the Big Y. The main suggestion for improvement is to focus the attention on the incoming parts because relevant improvements can be achieved in them. Firstly, it should be appropriate to perform a well defined P-FMEA on the manufacturing process of the incoming parts in order to find the main sources of variation, and increase the process capability. A DOE will allow understanding how robust is the process, as soon as the noise factors in the incoming parts (sub assembly) welding phase are under control.