

UNIVERSIDAD EAFIT
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**Dynamic analysis methods for motorcycle
architecture evaluation: Hybridization kit
development**

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Abstract

In the field of renewable, clean, and highly efficient transport, different hybrid and electrical solutions have emerged to mitigate the environmental impact. Specifically for the motorcycle segment, most of the available solutions are 100% electric and oriented to replace to a large extent the existing fleet, giving way to new areas of research focused on conversion and hybridization. This initiative of development of a hybridization kit for a motorcycle with manual transmission seeks to promote these new emerging technologies by solving the technological problem that affects them.

The effort is related to explore the viability of the technology through the development and research of the main systems (Energy Storage System (ESS), Power-train System (PTS), Control System (CS)) of the hybridization kit. However, there is no evidence of a proper product development process or a method for assessing the impact of modifications on the dynamic of the vehicle. Therefore, this document presents a research process focused on the definition of a dynamic analysis method by designing a hybridization kit for a motorcycle to evaluate a product architecture that respects the stability and maneuverability ranges.

Two case studies were developed through VDI guideline 2206. The method is implemented in stages of requirements definition to obtain relevant information through a reverse engineering process and in stages of detailed design to evaluate the stability of the modified motorcycle. The result is two different hybridization kit architectures that meet the stability analysis and could become a solution to the environmental problem generated by this segment.

Keywords: Dynamic analysis method, Electric kit, Hybrid Motorcycle, Mechatronic Product Development, VDI Guideline 2206, Weave mode, Wobble mode .

Resumen

En el campo del transporte renovable, limpio y de alta eficiencia, diferentes soluciones híbridas y eléctricas han surgido para mitigar el impacto ambiental. Específicamente para el segmento de motocicletas, la mayoría de las soluciones disponibles son 100% eléctricas y proponen sustituir en gran medida la flota existente, lo que ha dado paso a nuevas áreas de investigación centradas en la conversión e hibridación. Con esta iniciativa de desarrollo de un kit de hibridación para una motocicleta de transmisión manual, se busca promover estas nuevas tecnologías emergentes a través de la solución de los problemas tecnológicos que las afectan.

En este campo, el esfuerzo ha sido encontrar la viabilidad de la tecnología a través del desarrollo e investigación de los principales sistemas (Energy Storage System (ESS), Power-train System (PTS), Control System (CS)) del kit de hibridación. Sin embargo, no hay pruebas de un correcto proceso de desarrollo de producto ni de un método que evalúe el impacto de las modificaciones sobre la dinámica del vehículo. Por lo tanto, este documento presenta un proceso de investigación centrado en la definición de un método de análisis dinámico mediante el diseño de un kit de hibridación para evaluar una arquitectura de producto que respete los rangos de estabilidad y maniobrabilidad.

Se presentan dos casos de estudio desarrollados a través de la *VDI guideline 2206*. El método es implementado en etapas de definición de requerimientos para obtener información relevante a través de un proceso de ingeniería inversa y en etapas de diseño de detalle, para evaluar la estabilidad de la motocicleta modificada. El resultado, son dos arquitecturas diferentes de kit de hibridación que cumplen con los análisis de estabilidad y que podrían convertirse en una solución para el problema medioambiental generado por este segmento.

Palabras Clave: Método de Análisis Dinámico, Kit eléctrico, Motocicleta Híbrida, Desarrollo de Productos Mecátronicos, VDI Guideline 2206, Modo Weave, Modo Wobble .

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Chapter 1

Introduction

1.1 Problem Definition

Environmental pollution is a current problem that affects most of the countries of the world and is caused mainly by the burning of fossil fuels by mobile sources. In Colombia, as in some Asian countries (e.g., Thailand, Vietnam, Indonesia, Malaysia, China, India, and Pakistan), the automobile fleet increase has exerted pressure on public roads, which has led users to acquire two wheeler-vehicles with characteristics that can be adapted to road congestion problems, but at the same time, emitting high levels of pollutant gases.

Motorcycles have become an alternative to mobility for rural and urban areas reachable for the majority of the population (ANDI, 2017). Currently, this segment represents 57 % of the country fleet, meaning around 8.5 million units (Ministerio de Transporte, 2019). Therefore, this transport solution has become the access for the mobility of people at the base of the social pyramid, and a solution for the reduction of poverty through the improvement of marginal sectors displacement, the increase of the automotive industry jobs, and the way to obtain social, health, and education services (ANDI & FENALCO, 2017; ANDI, 2017).

Unfortunately, evolution has put motorcycles like one of the primary pollution sources. Thus, in an attempt to change the approach toward sustainable mobility, protect population health, reduce dependence on non-renewable fuels, and mitigate the environmental impact, the country has taken preventive measures such as mobility restriction in rush hours and the promotion of Hybrid Electric Vehicles (HEV) and Electric Vehicles (EV) (ANDEMOS, 2017) (República de Colombia, 2017).

Specifically, for the motorcycle segment, most of the solutions are 100% electric and propose to replace the existing fleet, being affected by technological, economic, and social problems. Regarding technological problems, the available solutions have a limited range and long charging period. Concerning social problems, the acceptance of new technologies, and the insufficient charging stations

generate apathy in users. Finally, respect to economic issues, the high price of the technology creates an unfavorable price/benefit ratio for people who use the motorcycle only for transportation and even more as a means of work.

Therefore, with few available solutions, new research areas arise focused on the conversion or hybridization process of the current motorcycle fleet. The effort has been in-depth to find technology viability through the development of the technical components that make them up, and that could be categorized in three groups:

- Energy Storage System (ESS)
- Control System (CS)
- Power-train System (PTS)

In general, it is common to see the development of functional prototypes. Most of them implement electrical solutions through random modifications and without a structured process, as it is shown in Fig. 1.1.



Figure 1.1: Prototypes developed in cited researches. a) (Tong and Jwo, 2007) b) (Hsu and Lu, 2010)

The researchers still do not know, and there is not found in the research process of the use of a clear methodology that will guide the development process of this kind of mechatronic product nor a method that evaluates the impact of the modifications.

Therefore, this research proposes a motorcycle dynamic analysis method to evaluate if a hybridization kit architecture respects stability and maneuverability ranges. The VDI 2206, a guideline for the design of mechatronic systems is used for the process where the method is implemented in specific phases as part of the re-design process.

1.2 Research question

The context provided by the definition of the problem shows us the value of conducting research focused on incorporating dynamic analysis methods in a motorcycle re-design process. Therefore, to establish a clear research direction, the following research question has been established

- What is the motorcycle dynamic analysis method that should be used in order to evaluate the architecture of a motorcycle hybridization kit in a way that it respects the stability and maneuverability ranges?

1.3 Objectives

1.3.1 General objective

To define a motorcycle dynamic analysis method, through the design of a hybridization kit, to evaluate a product architecture that respects stability and maneuverability ranges.

1.3.2 Specific objectives

- To analyze the dynamic stability models, motorcycle hybridization process and mechatronic design/re-design methodologies, based on background and studies by leader authors to understand the variables and needs to define the method.
- To develop a motorcycle dynamic analysis method to evaluate products' architecture in motorcycles considering stability and maneuverability ranges
- To validate in practice the proposed method through the development of two different architectures of an electric kit for motorcycle hybridization.

1.4 Research Scope

The scope of this project aims to develop a motorcycle dynamic analysis method to validate in an existing knowledge base the design of two different architectures of a hybridization kit. In this sense, the research project delivers not only a method but also two tangible cases of study that are the result of the VDI 2206 methodology follow-up with the method proposed in specific phases.

1.5 Research Approach

The present research was carried out following an approach proposed by Horvath as Design Inclusive Research (DIR) (Horváth et al., 2007). This specific research approach offers the possibility to embed

design as a research means. Furthermore, it opens the opportunity to explore and create contextualized knowledge that can not be developed with other research approaches. This methodology divides the research process into three phases: (i) phase of explorative research actions, (ii) phase of creative design actions, and (iii) phase of confirmative research actions. (See Fig.1.2).

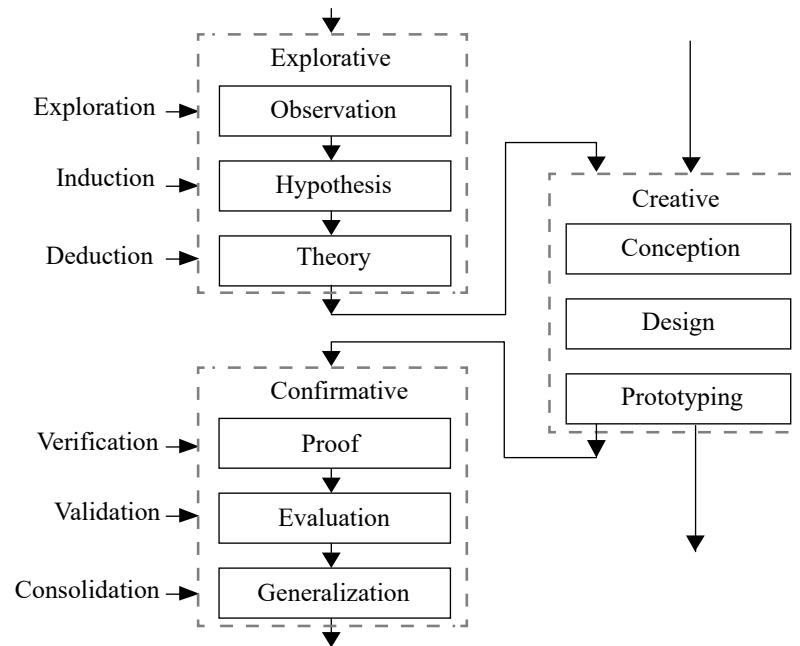


Figure 1.2: Major phases of Design Inclusive Research (Horváth et al., 2007)

1.6 Manuscript structure

This research is organized in three different phases: The first phase, composed by the background, the research problem, the literature review, the proposal and objectives to full-fill the research, is presented in Chapters 1 & 2. The second phase, composed of the description of the methodological re-design process, including the proposed motorcycle dynamic analysis method, is presented in Chapter 3. Finally, the third phase, which are two cases of studies where the method is evaluated, the proposal is developed, the data are interpreted, and the results are concluded, is presented in Chapters 4 & 5.

Chapter 2

Literature Review

Related researches found in the literature review are discussed in this chapter. The information has been divided into four sections:

- Section 2.1. *Mechatronic Design & Re-design Methodologies*, presents a general vision of the research approaches, followed by a more detailed study on methodologies used for the design/re-design of mechatronic products, product development applications, hybridization or conversion cases of study through methodology guide, and dynamic analysis methods considered in steps of the development process.
- Section 2.2. *Electric, hybrid and fuel cell vehicles*, presents a general classification and analysis of clean technologies, followed by a research focused on hybrid and plug-in hybrid motorcycles, and how they addressed the design, development, and sizing of the main components: Energy Storage System (ESS), Control System (CS) and Power-train System (PTS).
- Section 2.3. *Motorcycle Stability*, presents different studies, multi-body and dynamic stability models, and if they have been implemented as part of a methodological process.
- Section 2.4, presents a general conclusion of the literature research that includes the gaps found and how the topic will be addressed.

2.1 Mechatronic Design and Redesign methodologies

Design could be approached as a problem to be solved. In this field, the theory appears as a research approach where different models and methods are used to delineate design principles, design knowledge, and design practice (Ulrich and Eppinger, 2012). In the literature, several descriptive and prescriptive methodologies have been developed to facilitate the designer's task (Pahl and Beitz, 2013; Pugh, 1993; Ulrich and Eppinger, 2012; Otto and Wood, 1998)), nevertheless, they do not need to be

explicitly applied since all of them provide a step-by-step that serves as a guide for the process (Dieter et al., 2009).

Generally, the methods are divided according to the development process: (i) New development (new design), and (ii) further development (redesign). Both include the general design phases (conceptual, realization, detail), with the difference that the redesign methodologies initiate the process with available information of a product previously designed (Hehenberger, 2014; Asimow, 1962).

Today, with constant technological progress and the responsibility to satisfy customer demands in an industrial environment increasingly severe, products have evolved in mechatronic products linking different engineering domains. Hence, various methods appear to support development phases. On the one hand, the first methodological reference related to mechatronic product design arises in 1973 with the VDI 2222 (Guideline, 1973), and it has evolved to the VDI guideline 2206 (Gausemeier and Moehringer, 2003). The VDI distinguishes between the problem-solving process of the designer (micro-level) and the generic process related to design phases and corresponding product states (macro-level), systematically improving the process. From this approach, different formalized applications of modeling and methodologies adaptation appear to support conceptual design phases and also life cycle phases (e.g., Model-based systems design (Rau, 2002), RFLP method (Lesinski, 2015), Hierarchical Design Method (HDM) (Hehenberger, 2014; Mlambo et al., 2018)); nevertheless, they are considered as adaptations of the guideline that lend themselves to modifications in their structure.

On the other hand, related to redesign, Otto and Wood (1998) proposed a reverse engineering and redesign methodology focused on the steps needed to understand a previously developed product. The reverse engineering phase divides the process in two steps. First, product functionality is evaluated according to customer needs. Second, the form and function of the product are analyzed, a full disassembly process, and manufacturing and functional analysis are developed. Subsequently, the reverse engineering method continues as a design process with a modeling and analysis phase followed by a technical redesign, as a standard design methodology.

For this research focused on motorcycles (automotive industry) the design process could be considered as a redesign. As conclusions, the VDI2206 guideline is commonly used for the design and development of different mechatronic products, including vehicles with renewable energies (Neugebauer et al., 2009; Abd et al., 2007; Sanin and Velásquez-López, 2018; Ziemniak et al., 2009). Also, it was not possible to find a case of study of a motorcycle hybridization kit using VDI guideline 2206 nor a method considering dynamic analysis to evaluate product architecture as part of a methodology. Thus, considering the method as a rule for mechatronic products, the VDI2206 is chosen as the existing knowledge base where stages that link the information of the motorcycle as in input to the design process will be integrated.

2.2 Electric, Hybrid Electric and Fuel Cell Vehicles

The development of Internal Combustion Engine (ICE) vehicles, is one of the greatest achievements of the industry due to social growth contribution through transportation. In the last decades, the transition from ICE to clean solutions has become an attractive proposal since air pollution, global warming, and the rapid consumption of petroleum resources are now problems that need a solution (Ehsani et al., 2018). In this field of renewable, clean, and high-efficiency transportation, the main characteristics of vehicle design and manufacturing have changed. In the process, some drive-trains configurations are focused on improved efficiency and autonomy to fulfill customer requirements and to be able to compete with reliable ICE technologies.

These configurations can be classified into four different categories: Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicles (PHEV), Electric Vehicle (EV), and Hydrogen Fuel Cell Electric Vehicle (FCEV)

On the one hand, HEV and PHEV (see Figure 2.1) are configurations that allow to preserve or increase vehicle performance, reduced emissions and fuel consumption through the interaction between a ICE and an electric motor. In HEV, the ICE is the principal power source and the electric motor is used to assist at shortstops, and low speeds, and the charging process is carried out on-board using the ICE and the regenerative braking function. In PHEV, the electric motor is the first power source, and the combustion engine is used to assist the electric motor and extend the range. This kind of technology uses grid-supplied electricity and regenerative braking function, being more ecological compared to conventional hybrids.

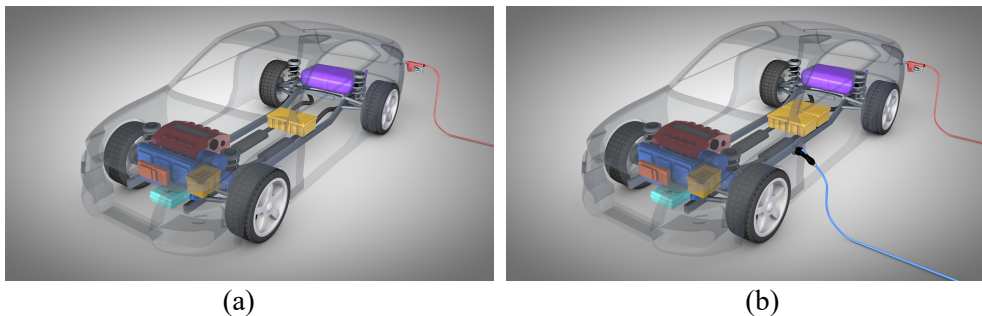


Figure 2.1: (a) HEV (b) PHEV (Hoekstra, 2018)

On the other hand, EV and FCEV (see Figure 2.2) are categories that always run with a single small and high-efficiency engine type (electric motor). In an EV the electricity is the only power source, and the battery size is significant to compete with the autonomy range of ICE and hybrid vehicles. The charging process is by grid-supplied energy and regenerative braking function. On the other hand, in FCEV, the battery size is small due to the hydrogen range extender. Unlike different

categories, this type of vehicle recharges only the tanks with hydrogen, which significantly minimizes the charging time.

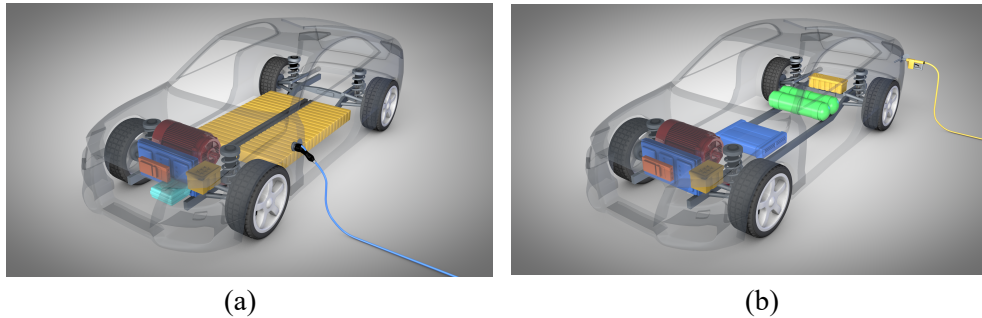


Figure 2.2: (a) EV (b) FCEV (Hoekstra, 2018)

2.2.1 Hybrid and Plug-in hybrid motorcycles

The study in clean and renewable technologies has been mainly in four-wheeled vehicles. However, due to the growth of the motorcycle fleet, the transition from ICE motorcycles to hybrid or plug-in hybrid motorcycles has become an attractive proposal. From a technical and economic point of view, the development has a high level of complexity. Today, it is a challenge to compete with the current non-renewable technologies, and that is why the research field has been approached from three specific knowledge groups (Energy Storage System (ESS), Control System (CS) & Power-train System (PTS)) in order to make this type of technology viable.

2.2.1.1 Energy Storage Systems (ESS)

ESS have a critical importance in Hybrid Electric Motorcycle (HEM) and Electric Motorcycle (EM) development. In recent years, the technological advancements in batteries, fuel cells, and other energy storage technologies have allowed a better vehicle performance and autonomy range (Khaligh et al., 2010). Properly design of a battery for automotive applications needs to take into account technical parameters such as, energy density, power density, lifetime, cost, and maintenance. Some researchers have focused their studies on defining those relevant technologies taking into account context and needs. Table 2.1 presents a summary of reported studies related to ESS for HEM.

In 2010, Khaligh et al. (2010) developed a state of the art of different battery chemistry for electric and hybrid applications. The most commonly adopted chemistry were: Lead-Acid, Nickel-Metal Hydride (NiMH), Lithium-Ion, Nickel-Zinc (NiZn), Nickel-Cadmium (NiCd), and Ultra-capacitors (UC). However, there is a preference of NiMH and Lithium-Ion batteries in commercial vehicles due to the price reduction that they have had in recent years and the reliability of the technology.

		(Khaligh et.al., 2010)	(Cao and Emadi, 2012)	(Weigl, 2014)	(Ferrari et.al., 2012)	(Morandin et.al.2015)	(Amjad et.al., 2010)
vehicle	Car						
	Motorcycle			•	•	•	•
	General	•	•				
Transmission	CVT			•			
	Manual					•	
Engine	HUB						•
	Base					•	
Architecture	Series					•	
	Parallel					•	
Control	Yes					•	
	Not						
Energy storage	LiPo						
	LiFePO4						
	Lithium ion	•					
	Lead acid		•				
	NiMH					•	•
	FC			•			
Prototype	UC			•	•		
	Yes		•	•		•	
	Not	•			•		•

Table 2.1: Energy Storage System (ESS) summary

In 2010, Amjad et al. (2011) presented an evaluation of three different battery types (Lead-Acid, NiMH and Lithium-Ion) in two different driving cycles: the Indian Driving Cycle (IDC) and the European Driving Cycle (ECE R40). The power and weight requirements of a ESS for a plug-in HEM are defined, and the results indicated for both driving cycles that the NiMH or Lithium-Ion satisfies voltage and current demand, and also weight and volume characteristics. The lithium-ion battery has 800 cycles less than NiMH, and the price per Wh is higher; therefore, NiMH is a good chemistry for hybrid solutions.

In 2012, Ferrari et al. (2012) conducted a study in order to choose a correct ESS for a HEM. For this application, a urban/ sub-urban WMTC and a Matlab code are proposed in order to compare three different technologies (UC, Lithium Polymer (LiPo), NiMH). The results show that the UC in a charge/discharge application represents the best solution in terms of durability, weight and volume. Unfortunately, this is the most expensive solution and it has not been applied as the only technology in HEV.

In 2012, Cao and Emadi (2012) proposed a new Hybrid Energy Storage System (HESS) based on Lead-Acid and UC technologies. Through a standard driving cycle (*Urban Dynamometer Driving Schedule* (UDDS)), the performance is evaluated, and the best technology is defined. The results satisfy the research requirements; nevertheless, lead-acid chemistry presents low energy density, power density, and life cycle, whereby, equaling other chemistry requires extra weight, a critical factor in

small vehicles such as motorcycles.

In 2014, Weigl (2014) proposed a HESS including three chemistry: UC, LiPo and Fuel Cell (FC). The HESS is compared with other mixed technologies through a *Worldwide Motorcycle Emissions Test Cycle* (WMTC) and the results do not show a significant difference compared to simpler technologies. Therefore, taking into account the chemical integration complexity, and factors such as weight and cost, mixed energy storage solutions are not very attractive for small vehicles such as HEM.

In 2015, Morandin et al. (2015) developed a comparison of ESS for a HEM application. The initial idea was to combine UC with other technologies; however, a NiMH battery (single chemistry) is chosen to reduce the cost, the complexity, and the weight of the product.

A ESS correct sizing is critical in a HEM development. The research of different chemistry identifies the NiMH and Lithium-Ion as the most common technologies for transportation applications, and the UC as a growing technology that would be useful in the development of hybrid ESS (See Table.2.2).

Chemistry	Nominal Cell Voltage (Volt)	Energy Density (Wh/kg)	Power Density (Kw/kg)	Cycle life (Times)
Lead-Acid	2	30-40	0,18	up to 800
Ni-Mh	1,2	55-80	0,4-1,2	up to 1000
Li-Ion	3,6	80-170	0,8-2	up to 1200
Li-Polymer	3,7	130/200	1-2,8	up to 1000
UC	2,5/2,7	2--30	4--10	over 1,000,000

Table 2.2: Battery characteristics presented in Cao and Emadi (2012)

Also, different driving cycles are proposed to size and compare various types of batteries during simulated conditions. This will be analyzed to identify similarities, get a driving cycle applied to the context, and hence, a correct battery sizing process. Finally, the prototypes presented a random distribution of the ESS, without analyzing how the shape, weight, and location affect the dynamic and motorcycle performance.

2.2.1.2 Control System (CS)

The CS represents the interaction between both Power Sources (PS). The most important concern is how to satisfy motorcycle power demand at the right moment, meanwhile accomplishing to reduce fuel consumption and emissions harmful to health. Different algorithms, control theories, and programming approaches are developed. Table 2.3 presents a summary of reported studies related to CS for HEM.

In 2007, Liu et al. (2007) proposed a Radial-Basis Function (RBF) Proportional Integrative Derivative (PID) controller with a fuzzy current limiter to increase the battery autonomy. A Matlab program was developed to compare the CS with and without a fuzzy current limiter, having positive results in battery savings. The development of this RBF-PID controller with fuzzy current limiter has been sim-

		(Liu et.al., 2007)	(Tong and Jwo, 2007)	(Hsu and Lu, 2010)	(Asaei et.al., 2010)	(Asaei and Habibidoost, 2010)	(Asaei and Habibidoost, 2013)	(Xiao et.al., 2013)
vehicle	Car							
	Motorcycle	•	•	•	•	•	•	•
	General							
Transmission	CVT		•	•	•	•	•	
	Manual							
Engine	HUB	•			•	•	•	•
	Base		•	•				
Architecture	Series							
	Parallel		•	•	•		•	
Control	Yes	•	•	•	•	•	•	•
	Not							
Energy storage	LiPo							
	LiFePO4							
	Lithium ion					•		•
	Lead acid		•	•	•		•	
	NiMH							
	FC							
	UC							
Prototype	Yes		•	•	•	•	•	
	Not	•						•

Table 2.3: Control system (CS) summary

ulated but not tested in physical prototypes, and it uses a DC servo motor as a PS that is characterized by a high cost and volume, non-viable in HEM applications.

In 2007, Tong and Jwo (2007) proposed a PID speed tracking CS with current-limiter and low battery protection. The CS manipulates a servo motor speed to match it automatically up to rear wheel rotation. The results allow identifying the PID control as a possible solution for the exchange of power transmission sources since it has a fast response time and low steady-state error.

In 2010, Hsu and Lu (2010) presented a Continuous Variable Transmission (CVT) motorcycle management system, including an Electronic Control Unit (ECU), a DC brushed motor and a motor controller. The CS gives three different driving modes: electric motor mode, engine/charging mode, and hybrid power mode, which are exchanged automatically according to the State Of Charge (SOC) and road conditions. This research presented a viable solution using driving modes to increase performance. Also, electronic development is simplified using independent controllers, allowing this CS as a feasible and low-cost solution.

In 2013, Asaei and Habibidoost (2013) developed a CS for a HEM. The CS is composed of two separate levels; in the upper one, the central unit is responsible for applying control signals, and in the lower one, the ICE ECU together with the electric motor controller are responsible for transmitting commands from the central unit to the engines. The CS considers motorcycle information to turn ON/OFF the propulsion systems, becoming a functional solution with low complexity and structural

modifications. Furthermore, Asaei and Habibidoost (2010) also implemented for the HEM mentioned above an energy control strategy through a simulation in ADVISOR. The simulation identifies the ICE inefficient regions to define a correct hybridization that achieves better fuel economy and fewer emissions, main functions to fulfill by HEM.

In 2013, Xiao et al. (2013) proposed a CS for a HEM with three driving modes: independent engine driving, independent motor driving, and engine-motor coordinated driving. A hardware-in-the-loop simulation applying a PID control algorithm is used to test and adjust details of complex real-time embedded systems, becoming a viable technique in the design process. The applied CS showed good results, and the PID control is commonly used in the development of HEM. In this way, it will be considered to adjust the speed of the engines.

The research shows that PID control algorithms are frequently used due to the effectiveness in the interaction between the ICE system and the electric motor, as well as some SOC models to know the battery voltage, current, and the vehicle's autonomy during a driving cycle. In some papers, a central CS that interacts with the specific controllers of each power source is presented, facilitating system interaction and the intervention degree on the motorcycle. For HEM control development, different driving modes, and security protections are presented to optimize the system; however, the CS topology on the motorcycle is not analyzed. Various factors will be taken into account for the CS design to affect the less as possible the motorcycle performance and stability.

2.2.1.3 Power-train System (PTS)

According to Ehsani et al. (2018) there are four different power-train interactions for HEV: series hybrid, parallel hybrid, series-parallel hybrid, and complex hybrid (See Fig. 2.3). The main difference is on the vehicle transmission and how the propulsion systems intervenes in a driving process. In this sub-section, it is presented how different researchers have developed this system using available technologies in terms of electric motors. Table 2.4 presents a summary of reported studies related to PTS for HEM.

In 2006, Sheu and Hsu (2006) developed a model of a parallel hybrid architecture, using some mechanical transmission components to integrate an ICE with a Brushless DC (BLDC) motor. The hybrid power-train can operate in four different modes to maximize the performance and reduce emissions; however, due to both power transmission systems, the components size and the mechanical losses, it is a challenge to implement this kind of hybrid power-train in small vehicles such as HEM.

In 2010, Hsu and Lu (2010) presented a parallel hybrid power-train to incorporate two propulsion systems in a HEM. Three different operation modes are proposed to maximize performance and to decrease pollutants. The architecture integrates or excludes the propulsion systems depending on the road conditions through a one-way clutch and chain drive mechanism. This solution, only implemented

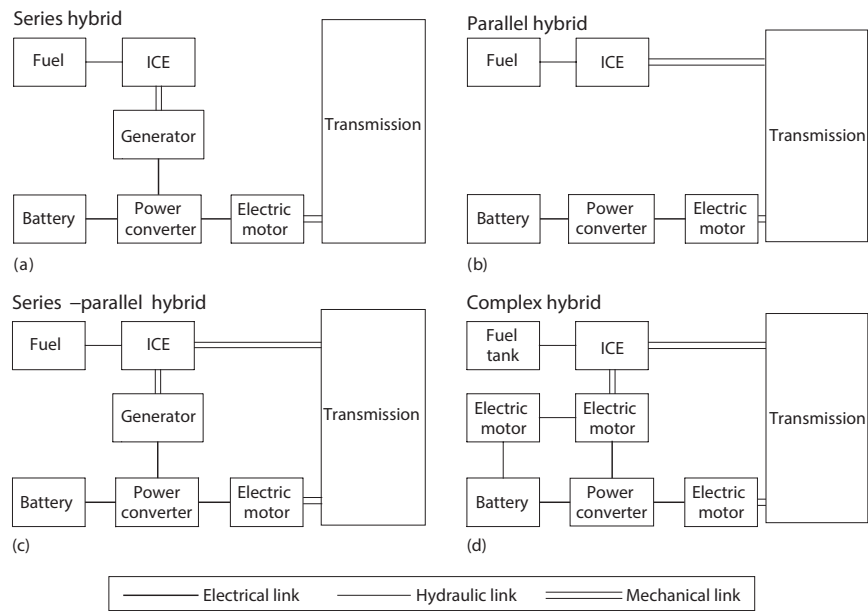


Figure 2.3: Hybrid Electric Vehicles Architecture (Ehsani et al., 2018)

		(Morandin et.al.2015)	(Chung and Hung, 2014)	(Asaei and Habibidoost, 2013)	(Sheu and Hsu, 2006)	(Hsu and Lu. 2010)
vehicle	Car					
	Motorcycle	•	•	•	•	•
	General					
Transmission	CVT		•	•	•	•
	Manual	•				
Engine	HUB			•		
	Base	•	•		•	•
Architecture	Series					
	Parallel	•	•	•	•	•
Control	Yes	•		•	•	•
	Not					
Energy storage	LiPo					
	LiFePO4					
	Lithium ion					
	Lead acid			•		•
	NiMH	•				
	FC					
Prototype	UC					
	Yes	•		•	•	•
	Not		•			

Table 2.4: Power-train System (PTS) summary

in CVT motorcycles, required high modifications being a not viable solution for manual bikes with space limitations.

In 2013, Asaei and Habibidoost (2013) designed a parallel hybrid architecture in a CVT motorcycle assembling a HUB electric motor in the front wheel. In this architecture, both wheels are involved independently in the power-train of the HEM; however, through a CS with different driving modes, the electric motor is integrated, avoiding a mechanical assembly with high intervention degree.

In 2014, Chung and Hung (2014) proposed a parallel hybrid architecture integrating an electric motor with an ICE system through a power split e-CVT. A planetary gearset and a dual one-way clutch are used, increasing the complexity and the number of mechanical components, and hence, the development in small vehicles such as motorcycles. However, with successful implementation in passenger cars, trucks, and buses allow identifying this solution as viable for CVT vehicles.

In 2015, Morandin et al. (2015) proposed a HEM replacing the original electric alternator with an electric machine. In order to improve motorcycle efficiency and space savings, a parallel hybrid architecture is developed. Such development, although amending considerably the ICE, appears as a viable solution for HEM since the new electric components have been optimized to maintain the original motorcycle shape.

Different PTSs are proposed. Nevertheless, it is familiar to prototyping in CVT motorcycles due to the secure interaction between propulsion sources. With an easy assembly and efficiency, HUB motors are preferred and installed under a parallel hybrid architecture where both engines intervene in motorcycle transmission. Although the primary purpose of all developments was to increase vehicle performance and reduce emissions, the prototypes presented do not have replicability. They have not been developed in a methodological order, and they give a random distribution without analyzing how the weight and location affect the motorcycle performance.

2.3 Motorcycle Stability

Motorcycle dynamics is an approach that has been studied for decades (Cossalter, 2006). The research has focused on theoretical studies, complex mathematical models, and experimental results explaining to a great extent, the motorcycle's behavior.

Usually, two-wheeled vehicles are unstable. They exhibit slightly damped oscillatory behaviors that can lead to serious compromise of the safety of the driver. These modes, named Wobble and Weave, are used in most of the researches to define stability and takes into account vehicle geometry parameters and weight distribution to determine stability and handling.

- *Weave*: It is a frequency of low oscillation (0-4 Hz) of the entire motorcycle, but mainly the

rear end. This mode is usually unstable at low speed, stable at the middle-speed range, and uncontrollable at high speed.

- *Wobble*: This is an oscillation of the front assembly around the steering axis that can become unstable at relatively low to medium speeds. For lightweight motorcycles, the frequency range is from 4Hz to 10Hz and is strongly influenced by the inertia of the front axle.

Table 2.5 presents a summary of reported studies related to motorcycle dynamic stability analysis.

		(Sharp, 1971)	(Cooper, 1974)	(Nishimi et al., 1985)	(Sharp and Limebeer, 2001)	(Limebeer et al., 2001)	(Evangelou ,2004)	(Evangelou, 2006)	(Evangelou et al.,2007)	(Evangelou, 2010)
Modes	Capsize	•								
	Wobble	•	•	•	•	•	•	•	•	•
	Weave	•	•	•	•	•	•	•	•	•
Equations	Yes	•	•				•		•	•
	Not				•	•		•		
Parameters	Yes	•	•				•		•	•
	Not				•	•		•		
Fixed control	Yes	•	•				•		•	•
	Not				•	•		•		
Stability analysis in motorcycle design applications	Yes							•		
	Not	•	•	•	•	•	•			•
Program	Autosim				•	•	•	•	•	•
	Matlab									
	Adams									
	N/A	•	•	•						

Table 2.5: Motorcycle Stability summary

In 1971, Sharp (1971) presented the first significant advance in the theoretical analysis of two-wheeled vehicles. The proposed model considers the motorcycle as two rigid bodies joined at the steering axis with rigid tires without frontal slip and with the freedom to sideslip, to yaw, and to roll. The analysis is developed at a constant speed, without inclination and aerodynamic factors to simplify complexity, obtaining a simplified dynamic model with which different cases can be analyzed, including natural oscillations (Wobble and Weave) at different conditions. In 1974, Cooper (1974) included the aerodynamic parameters in the stability model proposed by Sharp, to compare the natural motorcycle oscillations with and without the effect of drag and lift forces. Both models identify that lowering the center of mass is advantageous for practice since it has no impact on the Wobble mode and decreases the damping ratio of the Weave within the normal ranges. Also, the most significant influences come from the drag and lift forces, but they are not considerable variations.

In 1985, Nishimi et al. (1985) developed a mathematical model to analyze the straight running stability of a motorcycle, including an elaborated rider structural model. The effect of the rider in the parameters (Wobble and Weave) was measured experimentally at different speeds in different motorcycles, finding that the mass, the moment of inertia, and the longitudinal location of the mass

center has a considerable influence on both modes.

In 2001, Sharp and Limebeer (2001) proposed a motorcycle model for stability and control analysis based on previous literature information. AUTOSIM platform was used to develop a model and analyze straight running and cornering conditions. The model, which also considers weave and wobble mode, was regarded as the most general and more powerful than any other in the public domain. Furthermore, based on the model proposed by Limebeer et al. (2001), they developed a comprehensive study of the effects of acceleration and braking on motorcycles stability. The results showed that in negative inclination or braking on a level surface, the wobble mode is significantly destabilized, while positive inclination factor at a constant speed or accelerating on a level surface the damping of the wobble mode is substantially increased. Finally, acceleration, deceleration, and inclination factors have little effect on the damping or frequency of the weave mode.

In 2004, Evangelou (2004) developed a multibody dynamic software (AUTOSIM), where the motorcycle models proposed by Sharp (1971; 1994; 2001) are computerized to have a more comprehensive model that facilitates the solution of nonlinear and linear equations. With the model, the behavior of the Wobble and Weave modes under different conditions is analyzed. The results show that the Wobble mode is affected by the design and configuration of the front of the motorcycle while the Weave mode was more complex to isolate and resolve since the weight of the driver strongly influences it.

In 2007, Evangelou et al. (2006, 2007) proposed a mechanical steering compensator to improve the dynamic characteristics of the primary oscillatory modes of a high-performance motorcycle. The study was developed under computer simulations, which exploit a motorcycle model. Conventional steering damper benefits highly wobble mode performance but generates a destabilizing effect on the weave mode. As a result of this conflict, an optimization process is developed to identify the small range of damper coefficient values that could be used to improve both modes simultaneously.

In 2010, Evangelou (2010) proposed a variable geometry rear mono-shock suspension system that can be used to control high-performance motorcycles. The study includes a motorcycle simulation model that compares the conventional rear suspension with the variable geometry rear suspension. Results showed improvements in the damping of the weave mode for all speeds for a unaffected damping of the wobble-mode.

In previous studies, typical sophisticated models were applied to analyze the motorcycle behavior. In general, Wobble and Weave modes are explained in all researches to determine the stability in straight line and curve, and under conditions of positive, negative, and neutral inclination. The mass of the rider, the moment of inertia (front and rear frame), and the center of mass location are characteristics that determine the correct performance of the natural motorcycle oscillations. It has not been possible to find researches involving components that modify the motorcycle; however, for

a sports field, it has been possible to see the use of additional elements to improve stability. The two modes are substantially independent of each other, and there are no significant differences between the models with one or three degrees of freedom concerning the frequency values or damping ratios.

There is no evidence of dynamic stability researches in a methodological redesign process. The analysis is based on information of already manufactured motorcycles to verify or enhance stability parameters. Finally, it is possible to conclude that when incorporating the components of an electrical modification kit, the center of mass and inertia settings are going to be modified. With the information obtained in the dynamic stability section, the architecture will be defined, taking into account the behavior of the wobble and weave modes, to affect as little as possible the performance of the two-wheeled vehicle.

2.4 Observations on Literature Review

The works cited above have made a significant contribution to the fields that involve this research. First, section 2.1 allowed to identify the methodologies for the design and the redesign of mechatronic products and to determine that there is not an adequate redesign method that includes dynamic analysis tools to define product architecture of the two-wheeled vehicle. Section 2.2 allowed to define the main components of an electrical modification kit (ESS, CS & PTS) as well as the relevant technologies to be implemented, and the considerations necessary for the process of dimension and selection of the components. Finally, section 2.3 allowed to define the essential parameters to evaluate the dynamic stability in motorcycles to be able to analyze the location, shape, and weight of the main components, during the design process.

Regarding mechatronic design methodologies, different approaches have been developed; nevertheless, a method that evaluates the dynamic stability as part of a design/redesign process is an undeveloped field. In that sense, there is a great opportunity to implement a method based on the VDI guideline 2206 that incorporates in the design process stages, the stability evaluation for the definition of the shape, weight, and location of additional mechatronic components for motorcycles.

Chapter 3

Proposed Design Approach with Dynamic Analysis Tools

A motorbike is an innovative product with high complexity. Considering to redesign it through modifications or component integration is a challenge that requires the synergistic combination of different engineering domains. The VDI guideline 2206, proposed by Gausemeier and Moehringer (2003) is used as the knowledge base where the proposed dynamic analysis method is implemented. (See Fig. 3.1).

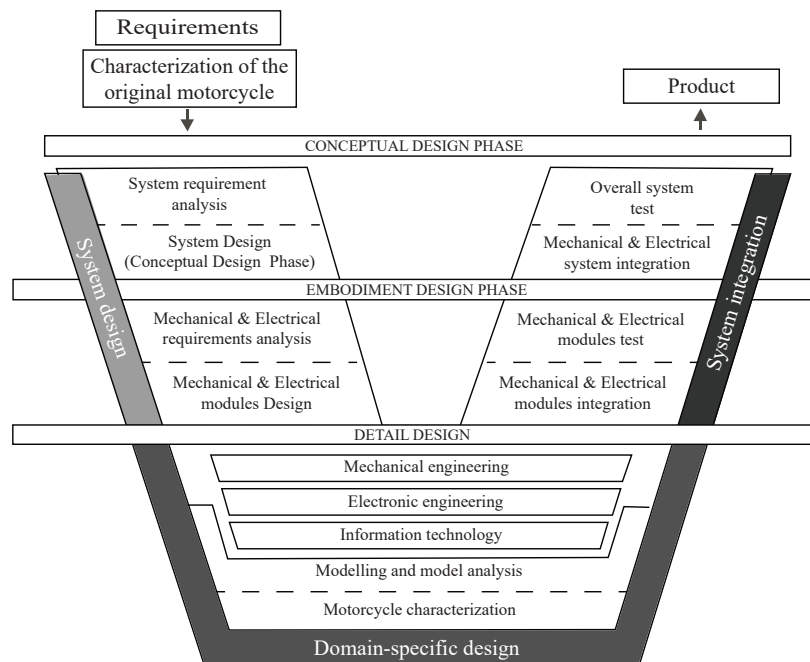


Figure 3.1: V-model on the macro level adapted from (Gausemeier and Moehringer, 2003))

The methodology begins with the design requirements definition usually established by the client, followed by the selection and characterization of the motorcycle. The method divides the process in three phases: 1- "System design" that sets a cross-domain solution concept with the main physical and logical characteristics of the redesign matter. 2- "Domain-specific design" that establishes detailed interpretations and calculations in a separate way for each technical system, and, finally, 3- "System integration" for assessing the performance of the overall system when the individual domains are integrated, taking into account different computer modeling and simulations systems.

3.1 Requirements

In a Product Development Process (PDP), the starting point is a set of requirements that the designer commonly acquires from the customer through qualitative tools. Those ideas, which are the design guidelines, need to be transformed into an engineering language, and that is where the House Of Quality (HOQ) of the Quality Function Deployment (QFD) method is commonly used, including the benchmarking room. The information obtained in the process is listed and categorized according to the Product Design Specification (PDS) categories proposed by Pugh (1993), and the result is the guideline document for the product design process (See Fig.3.2).

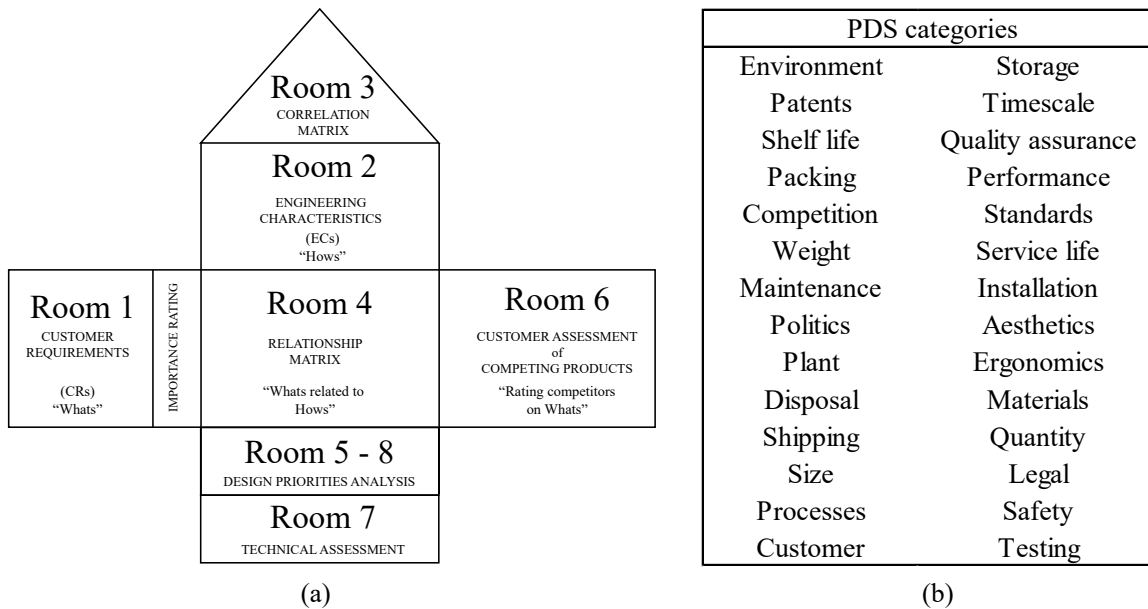


Figure 3.2: a) QFD, b) PDS categories

3.2 Characterization of the Original Motorcycle

The information is the differentiating factor between a design process and a redesign process. In this case, the motorcycle is the available information with which the process of design, sizing, selection, and location of the components will be started.

Usually, motorbikes are composed of several mechanical and electrical components. However, from a kinematic point of view, it can be analyzed in a more straightforward way using the geometric parameters presented in Figure 3.3.

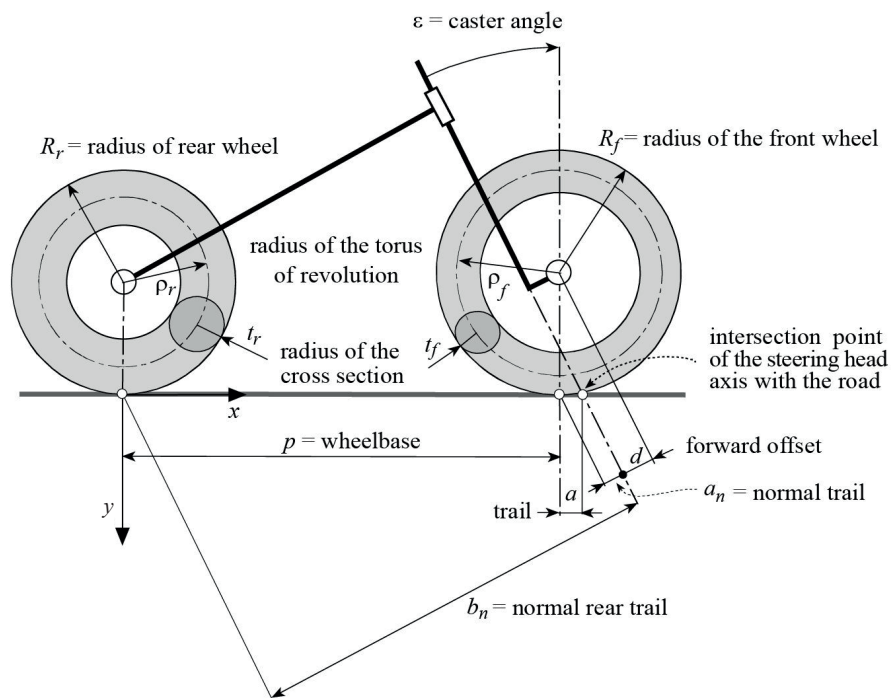


Figure 3.3: Geometry of a motorcycle (Cossalter, 2006)

Subsequently, all the information is used to develop a detailed Computer Aided Design (CAD) model, which will help to make decisions in the characterization process, and will allow defining values of variables of analysis (static, dynamic, stability), and in stages of the redesign process.

1. Static Analysis

The position of the center of mass is the first parameter that influences the motorcycle behavior and depends on the components distribution and their respective weights. To define its location, it is necessary to determine the (x, y) coordinates establishing as origin the contact point between the rear wheel and the ground. It is assumed that the center of mass is in the middle plane of the motorcycle due to weight symmetry, and there is no driver due to the complexity

of driving pattern analysis

For both parameters ($x = b$, $y = h$) is necessary to identify the load distribution under static conditions (N_{sf} , N_{sr}), the bike weight (mg) and some geometric values such as the wheelbase (p) and wheels radius (R_f , R_r) (See Eqs. 3.1 & 3.2). The longitudinal distance, is evaluated in a horizontal scenario while the vertical distance is evaluated in an inclined scenario where the front wheel is at a known distance (H), as it is shown in Fig. 3.4. For adequate behavior, the relationship between b/p and h/p should remain in a range between 0.35m to 0.51m and 0.3m to 0.4m, respectively (Cossalter, 2006).

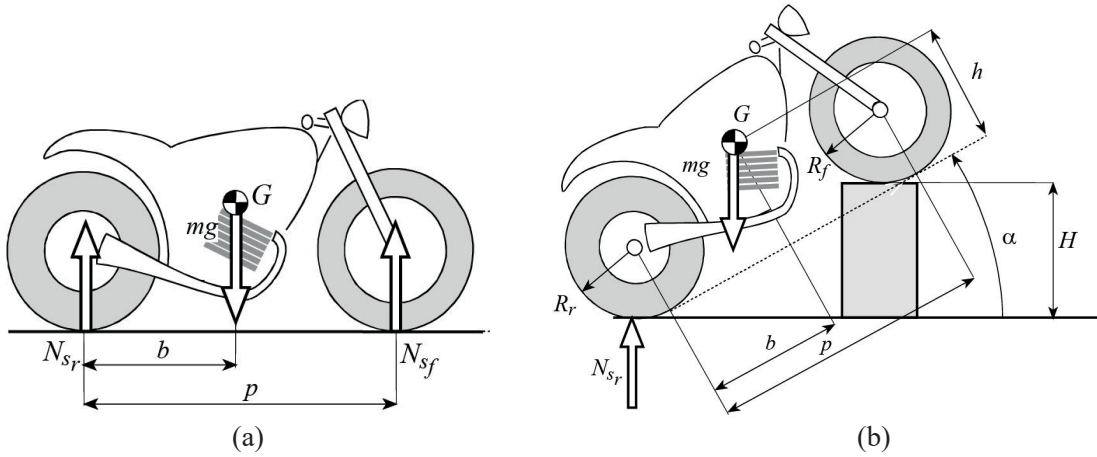


Figure 3.4: Position of the center of gravity a) Longitudinal b) Height (Cossalter, 2006)

$$b = \frac{N_{sf} \cdot p}{mg} = p - \frac{N_{sr} \cdot p}{mg} \quad (3.1)$$

$$h = \left(\frac{N_{sr} \cdot p}{mg} - (p - b) \right) \cot \left[\arcsin \frac{H}{p} \right] + \frac{R_r + R_f}{2} \quad (3.2)$$

The next parameters to analyze are the percentage of the distribution of load (See Eq. 3.3) and the relation between the front and rear trail (See Eqs. 3.4). For both analyses, the values vary according to the motorcycle type and functionality. For high-performance motorcycles, the results are always reaching the lower limits, while for street bikes, the values are more balanced, trying to improve the performance and the feeling of driving.

$$\frac{\%frontload}{\%rearload} = \frac{b/p}{(p - b)/p} \quad (3.3)$$

$$\begin{aligned}
 a_n &= a \cos \epsilon \\
 b_n &= (p + a) \cos \epsilon \\
 Rn &= (a_n / b_n)
 \end{aligned}
 \tag{3.4}$$

Regarding the percentage of the load distribution, the range for racing motorcycle is 50-70% front and 43-50% rear, and for touring / sports motorcycles are 43-50% front and 50-57% rear. In terms of the trail ratio, the range is approximately 4-8%, which also varies according to the motorcycle type and its characteristics. For racing motorcycle, the ratio is approximately 6%, for sport motorcycle from 6 to 6.5%, for touring motorcycle varies from 6 to 8% and for cruiser motorcycles from 5 to 6%.

2. Dynamic analysis (Rectilinear motion)

In the dynamic analysis, the behavior of the motorcycle in a straight line is evaluated, considering the effect of external forces such as the drag (F_D) and rolling resistance (F_r, F_f). The Free Body Diagram is presented in Figure 3.5.

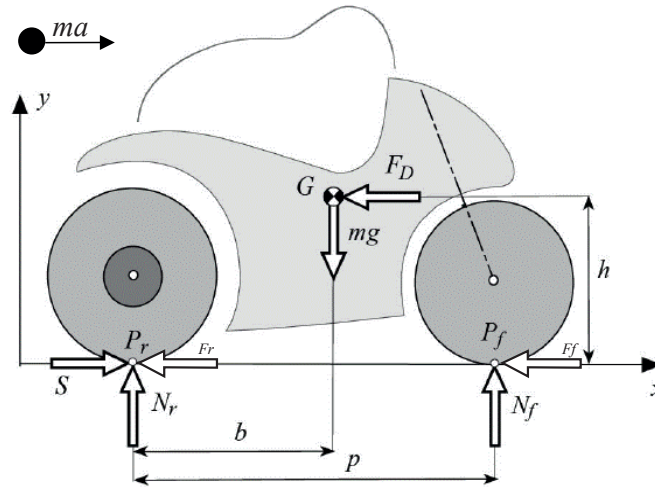


Figure 3.5: Dynamic (Cossalter, 2006)

- Equation of motion for horizontal forces

$$S - F_r - F_f - F_D = ma \tag{3.5}$$

- Equation of motion for vertical forces

$$mg - N_r - N_f = 0 \tag{3.6}$$

- Moment equation with respect to P_f

$$-N_r(p) + mg(p - b) + F_D(h) = -mah \quad (3.7)$$

The equations allow to determine the unknown values of maximum traction and maximum acceleration in the most critical cases, analyzing how the motorcycle performance is affected when the original architecture is modified.

- In the case of wheelie, it is assumed that $N_f = 0$ and $N_r = mg = w$, that is the front tire is on the verge of leaving the ground. Initially, the drag force (F_D) is calculated and later, the maximum acceleration (a) is determined, applying the equations 3.8 and 3.9.

$$S = \frac{wp + whC_{rr} - mg(p - b)}{h} \quad (3.8)$$

$$a = \frac{mg(p - (p - b)) - F_D * h}{mh} \quad (3.9)$$

- In the case of the maximum traction, it is assumed that $S = \mu_s * N_r$, $F_r = C_{rr} * N_r$ and $F_f = C_{rr} * N_f$. Normal reactions N_r and N_f , and the acceleration (a) are calculated applying the equations 3.10 to 3.13.

$$N_r = \frac{mg(p - b) - C_{rr}wh}{p - \mu_s h} \quad (3.10)$$

$$a = \frac{(\mu_s * N_r) - C_{rr}w - F_D}{m} \quad (3.11)$$

$$N_f = mg - N_r \quad (3.12)$$

$$S = \mu_s * N_r \quad (3.13)$$

3. Stability analysis

From the static and dynamic analysis, it is possible to determine, to a large extent, the performance of a two-wheeled vehicle. Nevertheless, it is necessary to characterize the ICE functionality through experimental dynamometer analysis, and to assess the maneuverability/handling through the slightly damped oscillatory behaviors (Wobble & Weave) that have a direct relation with the safety of the driver under driving conditions.

- **Wobble (One degree of freedom)**

For this mode, the front end is assumed as the only motorcycle component. The equation of equilibrium must be found in the rotation axis to establish later the characteristic equation of second degree, and with it, the roots, the damping ratio, and the frequency to perform the analysis. For all cases, the damping ratio, ξ , and the frequency, ν , are defined respectively by equations 3.14 and 3.15:

$$\xi = \frac{cV + K_{\lambda f} \times a_n^2}{2V\sqrt{I_{Af}K_{\lambda f} \times a_n \cos\varepsilon}} \quad (3.14)$$

$$\nu = \frac{1}{2\pi} \sqrt{\frac{K_{\lambda f} \times a_n}{I_{Af}}} \times \cos\varepsilon \sqrt{1 - \xi^2} \quad (3.15)$$

Where, ($K_{\lambda f}$) is the front tire cornering stiffness; (I_{Af}) is the front frame inertia about steering axis, (c) is the damping coefficient of the steering damper, (V) is the speed, and (ε) is the caster angle. The natural frequency of the wobble mode should remain between 4 Hz and 10 Hz.

- **Weave (One degree of freedom)**

This mode can be influenced mainly by the position in the center of mass, the caster angle, and the trail of the motorcycle. The damping ratio and the frequency must be found by equilibrium on rotation around the steering axis. For all cases, the damping ratio, ξ , and the frequency, ν , are defined respectively by equations 3.16 and 3.17:

$$\xi = \frac{cV + K_{\lambda r} \times l1^2}{2V\sqrt{I_{Ar}K_{\lambda r} \times l1 \cos\varepsilon}} \quad (3.16)$$

$$\nu = \frac{1}{2\pi} \sqrt{\frac{K_{\lambda r} \times l1}{I_{Ar}}} \times \cos\varepsilon \sqrt{1 - \xi^2} \quad (3.17)$$

Where, ($K_{\lambda r}$) is the rear tire cornering stiffness; (I_{Ar}) is the rear frame inertia about steering axis, and (c) is the damping constant for the steering axis. The natural frequency of the weave mode should remain between 0 Hz and 4Hz.

The frequency and the damping coefficient for both modes should be analyzed for the motorcycle's speed range, and the results of the stability modes should be verified by ensuring that the obtained values remain in the ranges established in the literature (Cossalter, 2006).

3.3 System Design

The system design divides the process in two phases: A conceptual design phase and an embodiment design phase. Both are developed according to the theoretical design method proposed by Ulrich and Eppinger (2012).

3.3.1 Conceptual Design Phase

This phase begins clarifying the problem through the analysis of the Customer Requirements (CR) list and the PDS. The problem is decomposed to find the overall function of the product and to represent it as a single black box operating on material, energy, and signal flows. From the overall black box, the next step is to create a functional decomposition. The primary function is divided into sub-functions to develop a more specific description of what the elements of the product fulfill. At this point, there is a clear idea of the product functionality; thus, an external search is necessary to find existing solutions to the overall problem or sub-problems. The idea is to organize and synthesize all the information in a morphological chart for representing and exploring all the relationships and be able to generate the first design solutions.

Usually, the number of possible combinations exceeds the capacity of the design team. Thus, a screening process proposed by Ulrich and Eppinger (2012) is necessary to rule out the combinations that do not make sense through the compliance of some main CRs. The idea is to finally have few concepts to be refined in a concept-scoring matrix, where more detailed analysis and quantitative evaluations are developed to choose a single concept most likely to lead to product success.

In the concept-scoring matrix, the CRs are the selection criteria one more time. The team weights the relative importance of each criterion, and the weighted sum of the ratings determines the concept scores. A concept serves as the principal reference, and then are rated with a scale from 1 to 5, as it is shown in Table. 3.1.

		Concept							
Selection Criteria	Weight	1		2		3		4	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score
CR1									
CR2									
CR3									
CR4									
CR5									
Total Score									
Total Score Rank	0%								
Continue	(yes/not)								

Relative Performance	Rating
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

Table 3.1: Concept-scoring matrix scale (Ulrich and Eppinger, 2012)

The score for each concept is calculated by multiplying the scoring column by the criteria weight, according to equation 3.18. The total score for each concept is the sum of the scores.

$$S_j = \sum_{i=1}^n r_{ij} w_i \quad (3.18)$$

Where r_{ij} is the raw rating of concept j for the i th criterion, w_i is the weighted for i th criterion, n is the number of criteria and S_j is the total score for concept j .

One or more concepts may remain of the process. However, it is viable to analyze the results and modify values according to the team's criteria. In some ways, this is the point of no return, so it is necessary to be sure of the selected concept to start the embodiment design phase.

3.3.2 Embodiment Design Phase

The Embodiment Design Phase (EDP) starts with the review of the selected concept viability to verify if any detail has been overlooked, followed by a preliminary design of the modules that form the product architecture. For this task, Ulrich and Eppinger (2012) propose a four-step process for establishing the architecture.

1. Create a schematic diagram of the product.
2. Cluster the elements of the schematic into modules.
3. Create a rough geometric layout.
4. Identify the interactions between modules.

Through these steps, it is possible to define the modules, components, characteristics, and interactions; and they allow to establish rough shape, dimensions, type of architecture (integral or modular), flows (energy, information, and material) and other parameters that have strong influences in the development process. At this point, the motorcycle information and the PDS are taken into account to obtain a realistic and successful result.

Generally, a close interrelationship between function and form is known, and, in turn, a dependence with materials and methods of production (See Fig. 3.6). Therefore, crucial decisions cannot be taken lightly, and it is recommended that a multifunctional group develop the process by making the necessary iterations to obtain the desired result.

3.4 Domain-specific Design

The domain specific-design seeks to establish a detailed interpretation of each part of the product, taking into account technical variables and manufacturing processes. This phase divides the detail design into three different domains: mechanical engineering, electrical engineering, and information technology; where the modules and interfaces that generate synergy for correct operation are detailed.

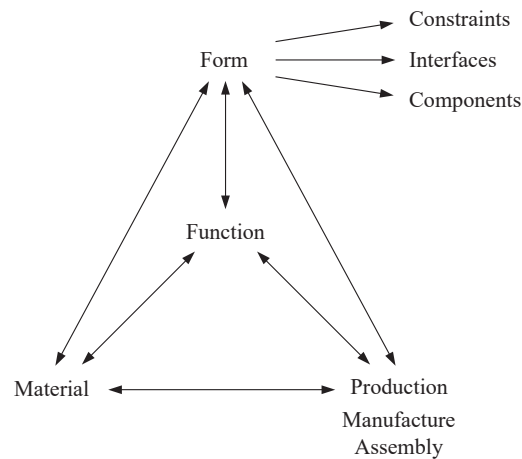


Figure 3.6: Interrelationship between function, form, material and production (Ulrich and Eppinger, 2012)

Furthermore, mathematical models and dynamic analysis are used to define the product architecture that does not affect motorcycle stability and maneuverability. The use of CAD / Computer Aided Manufacturing (CAM) tools standardizes, simplifies, and determines the attributes of the components such as dimensions, tolerances, weight, material, treatments, or surface finishes, and manages to establish values that generate a balance between functionality and cost. Finally, physical prototypes, engineering drawings, written documents, Bill of Materials (BOM), and the manufacturing process of parts are developed.

3.5 System Integration

On the right side of the V-model, the product modules are evaluated independently and as a system. Therefore, simulations, analysis, and tests are designed to validate the correct operation. The final result is a mechatronic product that does not necessarily have to be a finished manufactured product. From the beginning, the degree of maturity is established, for example, conceptual model or functional model; and under that specification, the product is evaluated, and it is determined if it is possible to continue or if it is necessary to iterate once more the methodology.

Chapter 4

Method Validation

In Colombia, the motorcycle is the most used mode of transport. Around 25 thousand bikes circulate daily, and mainly due to the traffic, the road conditions, the price-benefit, the simple operation, and maintenance, these numbers are increasing. For this research, a motorcycle *NKD 125c.c.*, from the *AKT Motos* company is selected as the object of study because it corresponds to a segment (Street/Sport) and an engine displacement (111c.c - 135c.c) very popular in the context of interest (Ministerio de Transporte, 2019).



Figure 4.1: AKT NKD 125c.c motorcycle

In this chapter, an electric kit for motorcycle modification is developed through VDI guideline 2206 applying the proposed motorcycle dynamic analysis method. Two case studies are proposed varying the product architecture. The design requirements and the original motorcycle characterization are presented in a cross way for both cases, and subsequently, the other phases are developed independently for each case.

4.1 Requirements of the Cases of Study

A multidisciplinary group of engineers (Physical, Mechanical, & Product Design) and potential users were gathered to discuss the product and its characteristics. Different qualitative tools were used to obtain relevant information for the redesign process, and the result were 15 Customer Requirements (CRs), rated from 1 to 5 according to the relevance for the PDP, and presented in Table 4.1.

Row #	Weight	CR #	Customer Requirements
1	5,0	CR1	The kit should make the motorcycle more ecological
2	4,0	CR2	The kit should make the motorcycle more efficient
3	4,0	CR3	The kit must reduce motorcycle operation cost
4	4,0	CR4	The kit must be minimally invasive
5	4,0	CR5	The kit must be affordable
6	5,0	CR6	The kit must be lightweight
7	3,0	CR7	The kit must be easy to assembly and disassembly
8	3,0	CR8	The kit must be small
9	5,0	CR9	The kit must support water and dust
10	5,0	CR10	The kit must have a guarantee
11	5,0	CR11	The kit must be safe
12	4,0	CR12	The kit must keep motorcycle driving ease
13	5,0	CR13	The kit must have a long lifespan
14	4,0	CR14	The kit must keep the motorcycle loading capacity
15	5,0	CR15	the kit must keep the motorcycle autonomy

Table 4.1: Customers Requirements for hybridization kit.

The CRs information is organized in Room 1 of the HOQ as the first step of the proposed approach, followed by Room 2 where the CRs are translated into Engineering Characteristics (EC)s, including units of measure and the direction of improvements. To facilitate definition, the characteristics have been divided in two aspects (modification kit and hybrid motorcycle), because some of them must be measured as a product independent of the motorcycle, while others need to be integrated to the motorcycle in order to be measured. Thus, those characteristics that were measured on the bike were identified with an asterisk (*).

The design team continues with Room 4 (Relationship matrix). Rows and columns are intersecting through symbols that represent an exponential range of numbers (e.g., 9,3,1, and 0) and indicate the strength of the association. The results show a typical pattern of a strong relationship between the CR and the specific EC that measures it; however, it is possible to identify other relationships of great importance for the redesign process. Subsequently, the design properties of the matrix are analyzed in rooms 5 and 8; the results determined that the most relevant ECs to be taken into account were EC3 (gas consumption), EC7 (product weight), EC5 (operation cost), and EC4 (autonomy). It is also necessary to give importance to characteristics as EC1 (CO emission per km) and EC2 (HC

emission per km), which focus on environmental aspects that have a medium relative weight but have high importance in the development. Characteristics as EC13 (extra operational functions), EC16 (ecological materials), and EC17 (gravity center height) were those of lower relative weight since they do not present a direct relationship with several CRs, however, they obtained a high relation with some high rated requirements such as CR1 and CR12.

Then, Room 3 (correlation matrix) is developed to identify the degree of interdependence among the ECs. The interdependence strength is indicated through symbols that represent a strong positive correlation, positive correlation, negative correlation, and strong negative correlation, as it is shown in Fig. 4.2.

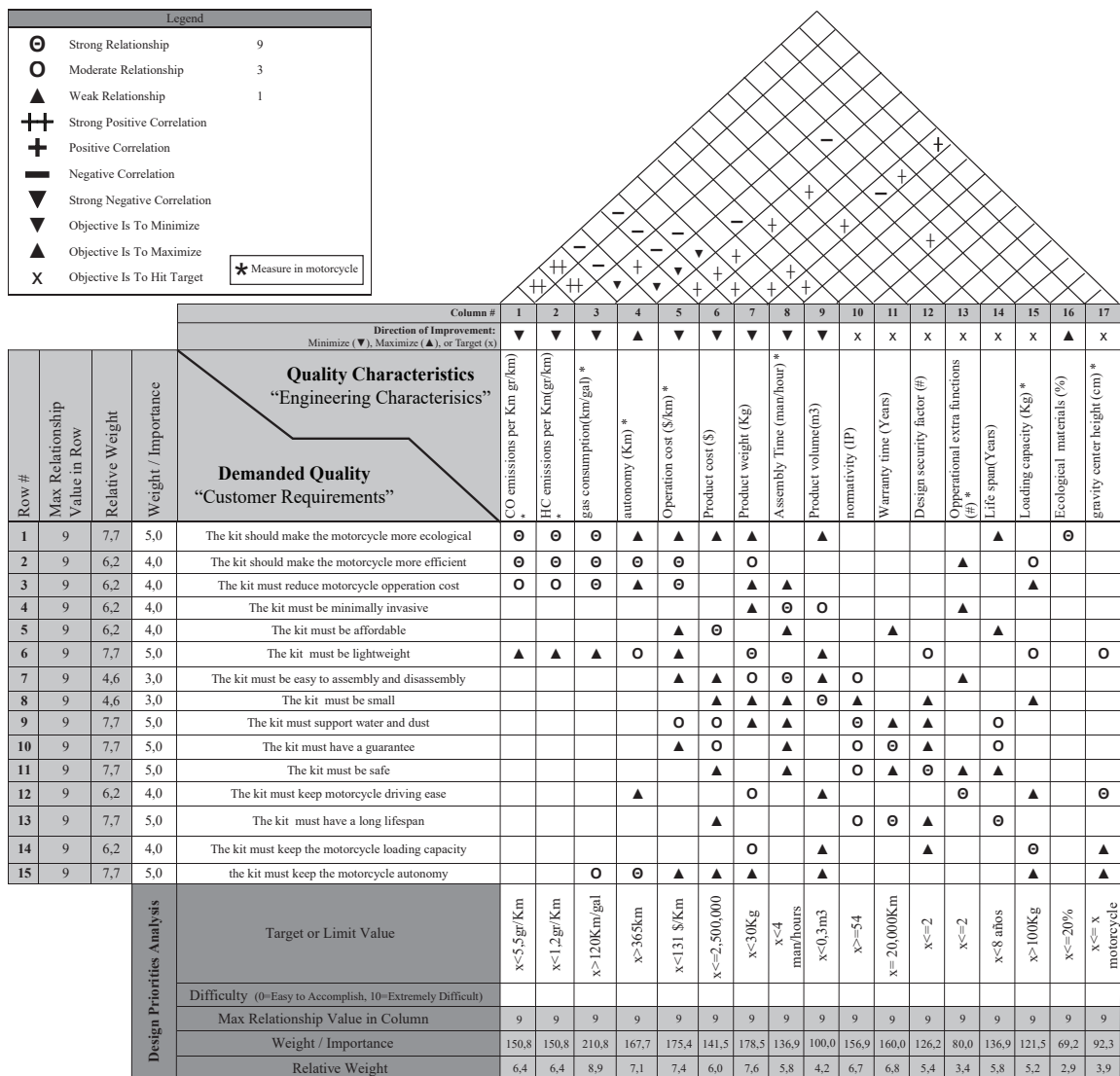


Figure 4.2: Quality Function Deployment (QFD) for hybridization kit (Polanía et al., 2018)

Finally, rooms 6 and 7 develop a competitive and technical analysis of the product versus the current products on the market:

- Electric kit for motorcycle conversion
- Electric motorcycle
- ICE motorcycle

On the one hand, the results of Room 6 (customer assessment of competing products) show the ICE motorcycle as a complete solution, robust in technical and security aspects only weak in environmental and cost-efficiency items. The conversion kit and the electric motorcycle as the most ecological, weak in technical CRs related to lightweight, affordability, autonomy, and assembly/disassembly process. Finally, the hybridization kit as an intermediate solution, which will allow improving technical and environmental problems of ICE systems, and autonomy/price problems of the electrical systems through the synergy of two different technologies (See Fig.4.3).

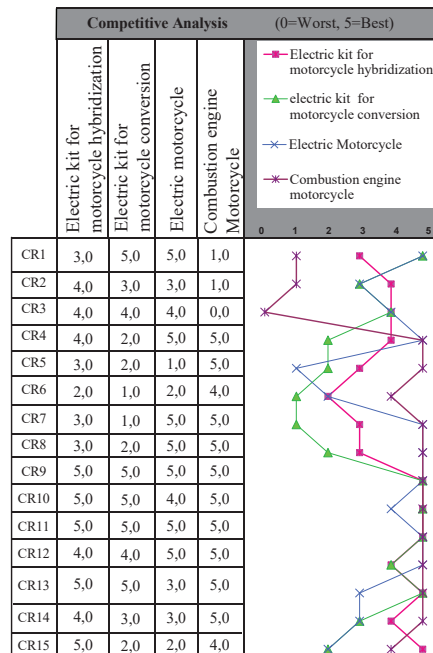


Figure 4.3: HOQ Room 6 - Competitive Analysis (Polanía et al., 2018)

On the other hand, Room 7 (technical assessment) is developed to define the rating in which each EC can be achieved in the hybridization kit and its direct competitors. The ICE motorcycle scored low only on the ECs related to emissions, fuel consumption, and operating cost. The 100% electric solutions scored best on environmental issues, and weak on autonomy, price, and durability characteristics; however, the results were variable on the other ECs. Finally, the hybridization kit, as

in the previous analysis, presents an intermediate solution, where it would improve the environmental characteristics of the motorcycle, and in turn, the motorcycle would enhance the rest of the technical aspects, as it is shown in Fig.4.4.

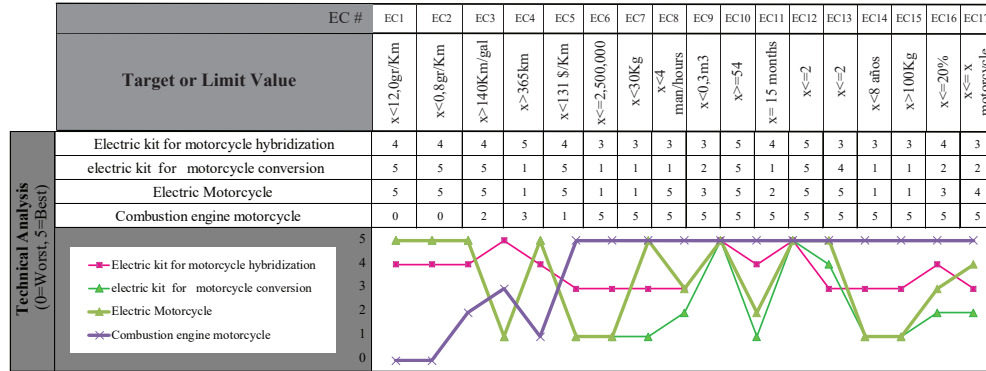


Figure 4.4: Technical Analysis - Room 7 (Polanía et al., 2018)

Finally, the information obtained in the HOQ is organized and categorized according to the PDS categories proposed by Pugh (1993), to have a guideline document for the next product development process (See. Table. 4.2).

Requirement Category	CR	EC	Units	Value	Priority
PERFORMANCE	CR1	EC1	Gr/Km	$x < 12,0$	7
		EC2	Gr/Km	$x < 0,8$	7
		EC3	Km/gal	$x > 140$	1
		EC16	%	$x = 20$	14
	CR2	EC5	\\$/Km	$x < 131$	3
		EC4	Km	$x > 365$	4
		EC3	Km/gal	$x > 140$	1
		EC2	Gr/Km	$x < 0,8$	7
	CR3	EC1	Gr/Km	$x < 12,0$	7
		EC3	Km/gal	$x > 140$	1
		EC5	\\$/Km	$x < 131$	3
	CR12	EC13	#	$x \leq 2$	13
		EC17	cm	$x \leq x$	14
	CR14	EC15	Kg	$x > 100$	11
	CR15	EC4	Km	$x > 365$	4
MANUFACTURING FACILITY	CR7	EC8	Man/hour	$x < 4$	9
PRODUCT VOLUME	CR4	EC8	Man/hour	$x < 4$	9
PRODUCT LIFE SPAN	CR13	EC11	Months	$x = 15$	5
		EC14	Years	$x < 8$	9
WEIGHT	CR6	EC7	Kg	$x < 30$	2
TARGET COSTS	CR5	EC6	\\$	$x = 2,500,000$	8
ENVIRONMENT	CR9	EC10	IP normativity	$x \geq 54$	6
SIZE	CR8	EC9	m^3	$x < 0,3$	12
DISPOSAL	CR10	EC11	Months	$x = 15$	5
SAFETY	CR11	EC12	#	$x \leq 2$	10

Table 4.2: Product Design Specifications (PDS) for hybridization kit (Polanía et al., 2018)

4.2 Characterization of the original motorcycle

The vehicle is analyzed from different technical aspects. First, a basic geometric parameters definitions is developed, from measurements and specifications supplied by the manufacturer, followed by a components characterization through technical data sheet analysis and a complete motorcycle disassembly (AKT, 2011). Results are presented in Table 4.3.

Table 4.3: Geometric parameters of the original motorcycle

Radius of the front wheel (R_f)	0.263m
Radius of the rear wheel (R_r)	0.266m
Wheel base (p)	1.27m
Caster angle (ε)	27 °
Trail (a)	0.094 m
Forward offset (d)	0.049 m

Subsequently, a detailed CAD of the motorcycle is developed using SolidWorks® to have a starting point for the re-design process and architectures evaluation (See Fig.4.5). The precision level is 99%, which means that some peripheral elements were not taken into account; however, they were weighted to determine the difference between the CAD model and the original motorcycle (See table.4.4)

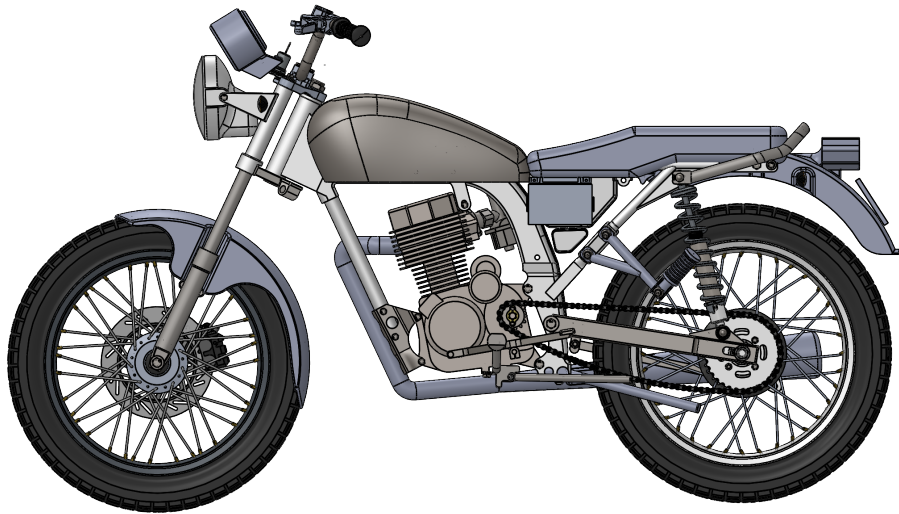


Figure 4.5: Original Motorcycle CAD

This characterization serves as a starting point for different phases in the PDP. Below, some analysis were developed to define other motorcycle parameters and to refine the CAD model, and subsequently, technical aspects such as shape, weight, and location of the components were evaluated.

Table 4.4: Components weight of the original motorcycle

Components/Assembly	Real weight (<i>kg</i>)	CAD weight (<i>kg</i>)
Front assembly		
Front wheel assembly	7.138	7.258
Front suspension	4.190	4.195
Triple tree	1.639	1.678
Handlebar	0.920	0.876
Screws & Accessories	4.872	4.859
Rear assembly		
Chasis	9.5	9.604
Internal Combustion Engine	30	30
Carburator	0.690	0.694
Air filter	0.680	0.680
12V 6.5Ah battery	2.280	2.295
Swingarm	2.7	2.796
Rear shocks	3.08	2.914
Rear wheel assembly	10.614	10.71
Gas tank	3.450	3.450
Seat	1.3	1.450
Screws & Accessories	12.614	13.15
Not included	2.33	-
Total weight (<i>kg</i>)	98	96.6

4.2.1 Static analysis

In this subsection, the location of the center of mass is calculated applying the equations 3.1 and 3.2. The load distribution for both cases is calculated with the equation 3.3. The normal rear and normal trails, under static conditions, are calculated with the set of equation 3.4. The results, which are essential for motorcycle stability, are within the ranges established by the literature, and correspond to a motorcycle of the street/sports segment, as it is shown in Table. 4.5.

4.2.2 Dynamic analysis (Rectilinear motion)

Initially, the behavior of the combustion engine is evaluated through a (Dynamite) test that gives information related to the Air Fuel Ratio (AFR) throughout the RPMs range, Torque (ft-lb) and Power (HP). The results are presented in Figure 4.6 and show that the motorcycle does not work in

Table 4.5: Center of mass, trail & weight analysis of the original motorcycle

	Original bike	Original CAD model
Wheel base (p)	1.27m	1.254m
Longitudinal position of the center of mass (b)	0.54m	0.55m
Height of the center of mass (h)	0.47m	0.49m
Front weight (W_f)	41.5Kg	42.4Kg
Rear weight (W_r)	56.5Kg	54.2Kg
Total weight (W_r)	98Kg	96.6Kg
Load distribution (rear-front)	57%- 43%	56%- 44%
Normal trail (a_n)	0.08m	0.08m
Normal rear trail (b_n)	1.22m	1.20m
Trail ratio (R_n)	5.09%	5.47%

the standard ratio (14.7:1). In first and second gears it shows a high presence of air (leaner mixture), while from the third to the fifth gear it shows a high presence of fuel (rich mixture). This means that the motorcycle is inefficient, in a leaner mixture gives more power, but increase engine temperature, and in a richer mixture provides cooler temperature in the engine, but less power and high un-burn fuel.

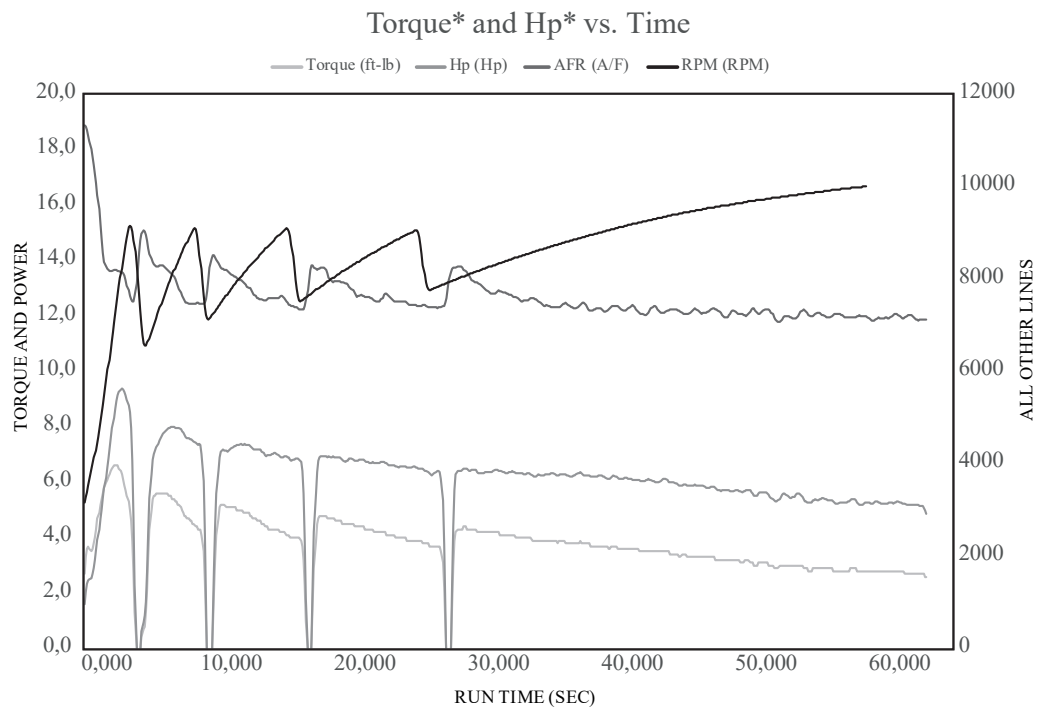


Figure 4.6: Air Fuel Ratio (AFR) of the original motorcycle

After that, the critical scenarios of maximum acceleration (wheelie) and maximum traction are performed. In the scenario of a wheelie (assumption 1), represented by the equations 3.8 to 3.9, the results presented in Table 4.6 indicate that the acceleration and traction necessary to lift the front tire from the ground cannot be fulfilled by the motorcycle, making it stable in rectilinear motion.

Parameter		Original bike	Original CAD	Unit
$S = \frac{wp + whC_r - mg(p - b)}{h}$	s	1130.09	1087.10	<i>N</i>
$a = \frac{mg(p - (p - b)) - F_D h}{mh}$	a	11.34	11.06	<i>m/s2</i>
$N_r = \frac{mah + mg(p - b) + F_D h}{p}$	Nr	961.47	947.83	<i>N</i>
$S = \mu_s * N_r$	Smax	769.18	758.27	<i>N</i>

Table 4.6: Original motorcycle. ASSUMPTION 1 - Wheelie ($N_f = 0, N_r = w$)

In the scenario of maximum traction (assumption 2), represented by the equations 3.10 to 3.13, the results presented in Table 4.7 express normal parameters of the maximum traction and acceleration to which the motorcycle arrives taking into account its original characteristics and the load distribution without fluids neither a passenger.

Parameter		Original bike	Original CAD	Unit
$N_r = \frac{mg(p - b) - C_r wh}{p - \mu_s h}$	Nr	774.21	761.87	<i>N</i>
$a = \frac{(\mu_s * N_r) - C_r w - F_D}{m}$	a	6.12	6.11	<i>m/s2</i>
$N_f = mg * N_i$	Nf	187.17	185.86	<i>N</i>
$S = \mu_s * N_r$	S	619.37	609.50	<i>N</i>

Table 4.7: Original motorcycle. ASSUMPTION 2 - Maximum traction ($S = \mu_s * N_r$)

4.2.3 Stability analysis

Models of slightly damped oscillatory modes are developed. In the calculation, the motorcycle CAD and the set of equations 3.14 to 3.17 are used to define the moment of inertia around the steering axis of the front and rear assembly. The modes are evaluated independently in a speed range of 0 to 100 km/h, which corresponds to the allowed mechanical range.

For both modes of weave and wobble, the frequency for the damped system rises as the speed

increases, and the damping ratio decreases (See Fig. 4.7). In wobble mode, the frequency values are between 4.63 - 7.05 Hz, while in weave mode are between 1.19 - 2.39Hz, which means the results are within normal ranges and represent a lightweight motorcycle (See Table. 4.8).

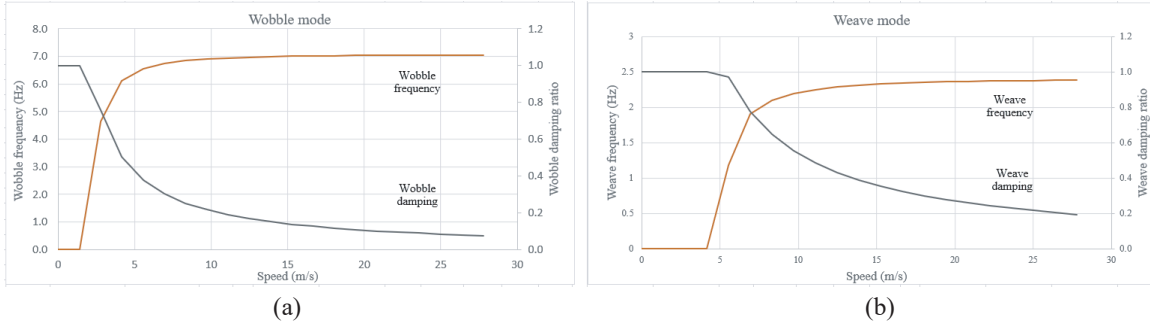


Figure 4.7: Original motorcycle. a) Wobble mode b) Weave mode

Damping ratio	V(Km/h)	V(m/s)	ζ	ν
$\zeta = \frac{cV + K_{\lambda f} a_n^2}{2V\sqrt{I_{A_f} K_{\lambda f} a_n \cos \epsilon}}$	0	0	-	-
	5	1.39	-	-
	10	2.78	0.76	4.63
Frequency for the damped system	15	4.17	0.50	6.11
$\nu = \frac{1}{2\pi} \sqrt{\frac{K_{\lambda f} a_n}{I_{A_f} \cos \epsilon} (1 - \zeta^2)}$	20	5.56	0.38	6.55
	25	6.94	0.30	6.74
	30	8.33	0.25	6.85
	35	9.72	0.22	6.91
Front assembly moment of inertia around the steering axis	40	11.11	0.19	6.95
	45	12.50	0.17	6.97
$I_{A_f} = I_{g_f} + M_f * B_f^2$	50	13.89	0.15	6.99
	55	15.28	0.14	7.01
	60	16.67	0.13	7.02
	65	18.06	0.12	7.03
	70	19.44	0.11	7.03
	75	20.83	0.10	7.04
	80	22.22	0.09	7.04
	85	23.61	0.09	7.05
	90	25.00	0.08	7.05
	95	26.39	0.08	7.05
100	27.78	0.08	7.05	
Typical frequency values range from 4 Hz for heavy motorcycles to 10 Hz for lightweight motorcycles.				

(a)

Damping ratio	V(Km/h)	V(m/s)	ζ	ν
$\zeta = \frac{cV + K_{\lambda r} l^2}{2V\sqrt{I_{A_r} K_{\lambda r} l \cos \epsilon}}$	0	0	-	-
	5	1.39	-	-
	10	2.78	-	-
Frequency for the damped system	15	4.17	-	-
$\nu = \frac{1}{2\pi} \sqrt{\frac{K_{\lambda r} l}{I_{A_r} \cos \epsilon} (1 - \zeta^2)}$	20	5.56	0.97	1.19
	25	6.94	0.78	1.91
	30	8.33	0.65	2.1
	35	9.72	0.55	2.2
Rear assembly moment of inertia around the steering axis	40	11.11	0.49	2.25
	45	12.50	0.43	2.29
$I_{A_r} = I_{g_r} + M_r * l^2$	50	13.89	0.39	2.31
	55	15.28	0.35	2.33
	60	16.67	0.32	2.34
	65	18.06	0.30	2.35
	70	19.44	0.28	2.36
	75	20.83	0.26	2.37
	80	22.22	0.24	2.37
	85	23.61	0.23	2.38
	90	25.00	0.22	2.38
	95	26.39	0.20	2.38
100	27.78	0.19	2.39	
The natural frequency of this side-to-side motion is zero when the forward speed is also zero and ranges from 0 to 4 Hz at high speed.				

(b)

Table 4.8: Original motorcycle. a) Wobble mode b) Weave mode

From the characterization and the high degree of detail of the CAD model, it is possible to conclude that a motorcycle NKD 125c.c is a stable motorcycle. Static, dynamic, and stability results are within normal ranges. With this initial information, it is proposed to develop two case studies based on the VDI guideline 2206.

4.3 Case of Study 1

4.3.1 System Design - Conceptual Design Phase

For the first case of study, the primary function of the product was established as “transform electric energy into mechanical energy”. The inputs/outputs flows are related to ICE motorcycle information, the environmental/human factors, and energy/force flows produced in the process. A total of eight inputs flows (three energy/force flows, and six information flows) and four output flows, all of them, energy/force flows were identified, as it is shown in Figure 4.8.

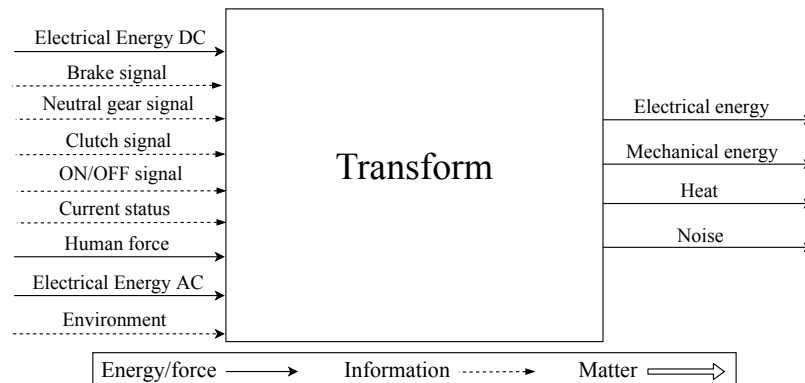


Figure 4.8: Black box for Case of Study 1

After that, a functional structure is proposed to break down a complicated design into manageable chunks, as it is presented in Figure 4.9. A total of 17 sub-functions are identified as well as the energy, matter, and information flows that interconnect them. Through this structure, a rough operation of the product and the relationship that it has with the motorcycle components are analyzed.

The method continues with a morphological chart developed to structure the problem of synthesizing different components that fulfill the same required function. With a total of 17 sub-functions and 47 solutions, a little less than 13.500.000 concepts are identified. However, it can be noticed that not all ideas are viable, so a screening process is performed with CRs as filters. First, concepts are evaluated according to CR5 (The kit must be affordable), filtering the results to less than 83.000 options. Then, they are filtered again according to the CR4 (The kit must be minimally invasive) and CR7 (The kit must be easy to assemble and disassembly), filtering the results 16 options. Finally, they are filtered according to CR12 (The kit must keep the motorcycle driving ease), leaving a total of 8 possible concepts, as it is shown in Appendix A.0.1.

Finally, with the eight concepts, a concept-scoring matrix is developed to increase the resolution among competitors. The selection criteria are some of the technical CRs of the PDS chosen by the design group. In the results, concept 1 had the best score; however, it is essential to take into account concept 2 as it obtained a high score in the matrix (See Table 4.9).

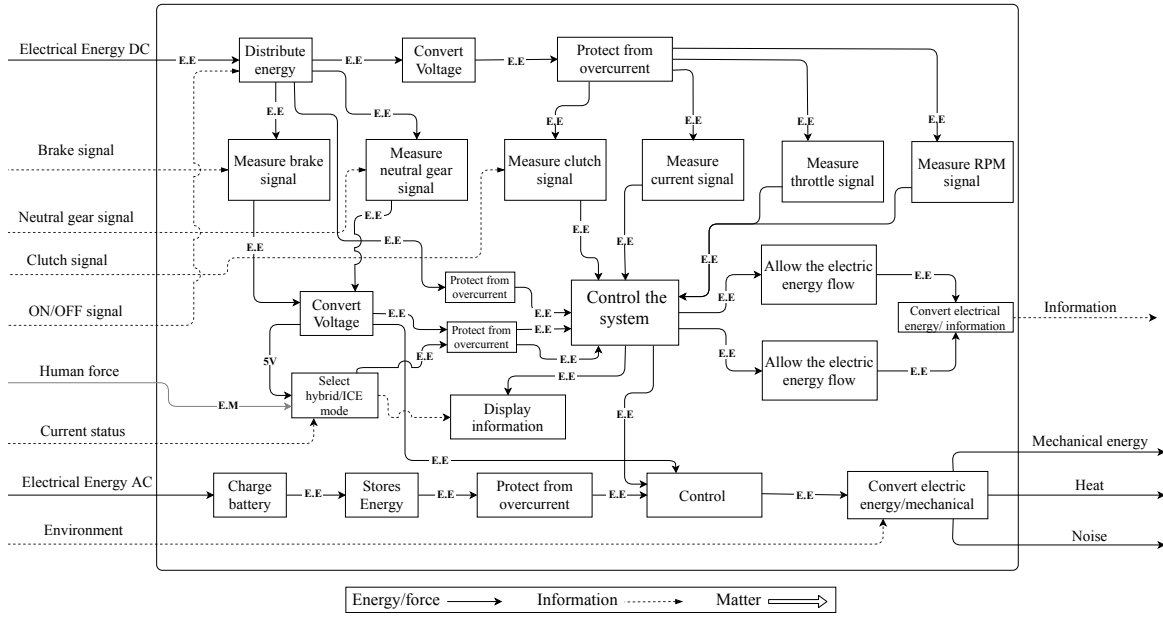


Figure 4.9: Functional Structure for Case of Study 1

Selection Criteria	Weight	Concept															
		1		2		3		4		5		6		7		8	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
The kit must be affordable	17%	4	0.68	3	0.51	3	0.51	2	0.34	5	0.85	4	0.68	4	0.68	3	0.51
The kit must be minimally invasive	20%	5	1	4	0.8	4	0.8	3	0.6	4	0.8	3	0.6	3	0.6	2	0.4
The kit must be easy to assembly and disassembly	18%	5	0.9	3	0.54	4	0.72	2	0.36	4	0.72	2	0.36	3	0.54	1	0.18
The kit must have a long lifespan	30%	4	1.2	5	1.5	3	0.9	4	1.2	3	0.9	4	1.2	2	0.6	3	0.9
The kit must support water and dust	15%	4	0.6	5	0.75	3	0.45	4	0.6	3	0.45	4	0.6	2	0.3	3	0.45
Total Score		4.38		4.1		3.38		3.1		3.72		3.44		2.72		2.44	
Total Score Rank	100%	1		2		5		6		3		4		7		8	
Continue		Develop		-		-		-		-		-		-		-	

Table 4.9: Concept-scoring matrix for Case of Study 1

4.3.2 System Design - Embodiment Design Phase

The product to be designed is directly related to an existing product; for that, a slot-modular architecture with specific functions and interactions between modules is the best option. A schematic diagram of the product, including a chunks clustering, the concept solution, and energy/force flow specification is developed, and presented in Figure 4.10. Seventeen chunks are clustered in three groups (CS, ESS & PTS) taking into account factors such as portability of the interfaces, localization of change, accommodating variety, and function sharing.

Subsequently, a rough geometric layout of the product is created locating the principal groups in the motorcycle original architecture, as it is presented in the Figure 4.11. At this point, the use of an electric HUB motor is defined due to the high efficiency and ease of assembly; and it is decided to locate the motor in the front wheel since the level of intervention is minimal. On the other hand, to

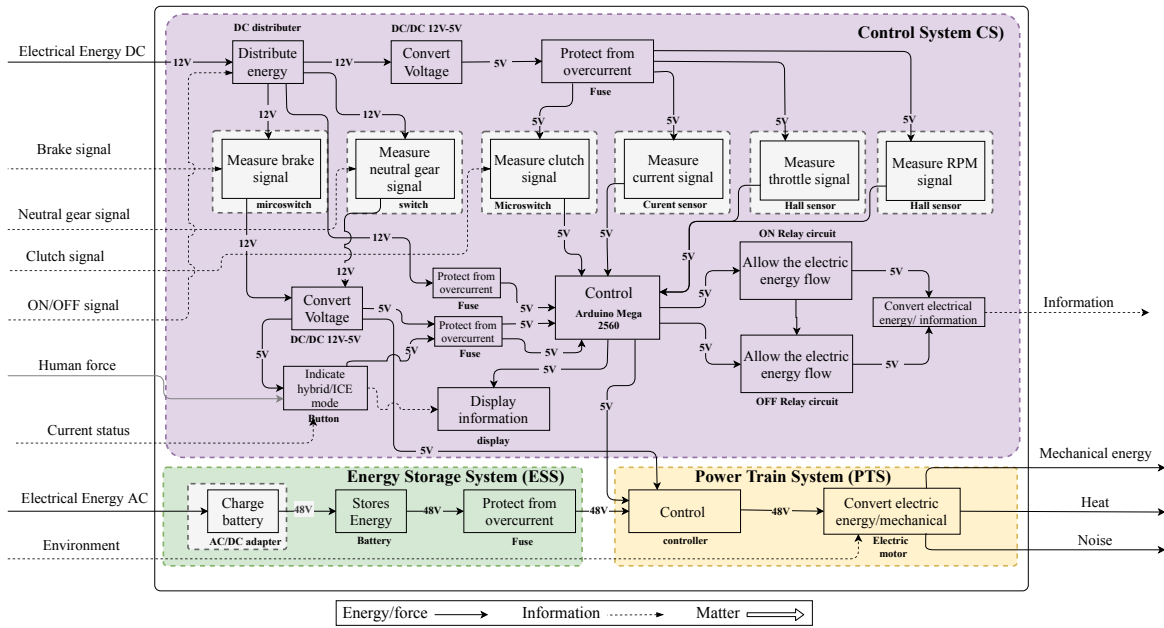


Figure 4.10: Schematic of the product for Case of Study 1

compensate the weight added to the front of the motorcycle, it is decided to locate the battery in the rear zone simulating a top-case, and the control system near to the handlebar since the motorcycle's electric wiring is located mainly into the front light.

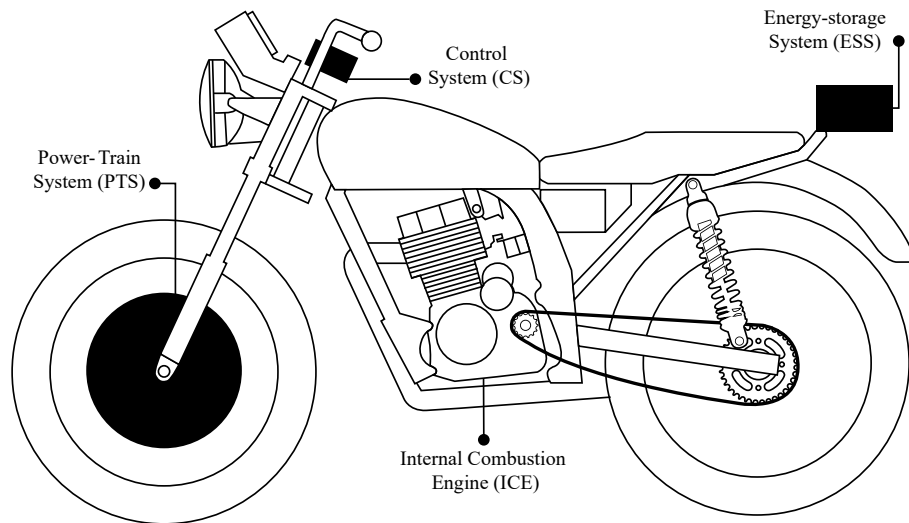


Figure 4.11: Architecture for Case of Study 1

4.3.3 Domain-specific Design - Mechanical engineering

The physical main components (ESS & PTS) are sized through mathematical calculations in real conditions of a driving cycle (See Appendix A.0.2). As basic information, the AFR data set and the original motorcycle characterization process are used to define the sections of greater ICE inefficiency in the driving cycle. The results determine as the best option a parallel hybrid architecture where the electric motor replaces the first gear in a speed range between 0 to 20 Km/h, as it is shown in Figure 4.12.

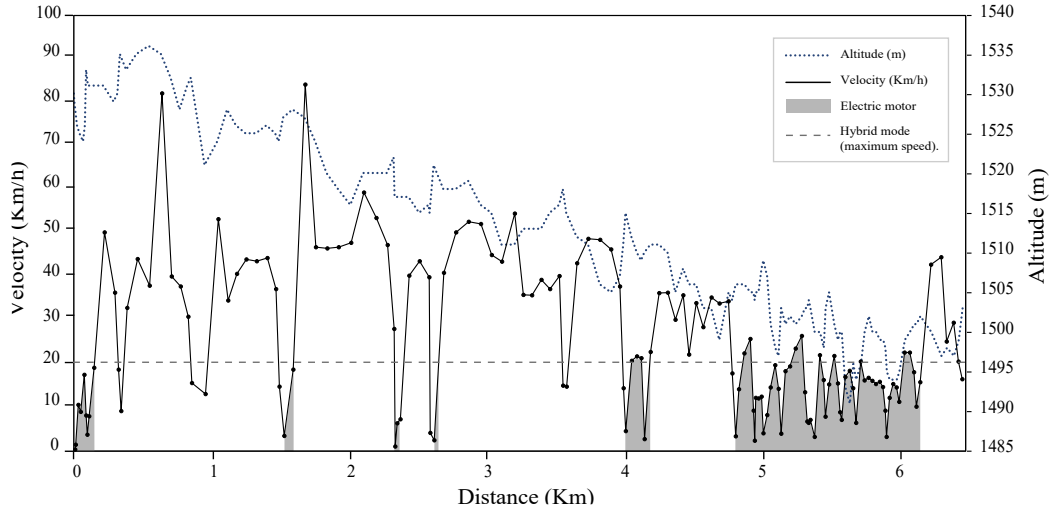


Figure 4.12: Driving cycle

Under this assumption, the power (W) and the energy (Wh) required to satisfy the cycle is calculated through the equation 4.1.

$$P_{out} = \frac{\vec{V}}{n} [m \cdot a + m \cdot g \cdot \text{sen}(\text{atan}(G)) + m \cdot g \cdot \text{cos}(\text{atan}(G)) \cdot Crr + \frac{1}{2} \cdot \rho \cdot Cd \cdot A \cdot (Vf - Vi)^2] \quad (4.1)$$

Where \vec{V} is the speed (m/s), n is the motor efficiency (%), m is the mass of the motorcycle (kg), a is the motorcycle acceleration (m/s²), g is the gravity acceleration (m/s²), G is the inclination factor (%), Crr is the rolling resistance coefficient, ρ is the air density (kg/m³), Cd is the air drag coefficient, A is the frontal area (m²), Vf is the final velocity (m/s), and Vi is the initial velocity (m/s).

The required information is presented in the table 4.10.

The results show that a motor of 1000W satisfies power conditions and a battery of 92 Wh fulfills the energy conditions. However, to have an autonomy around 40Km and to decrease the quantity of components to be installed, a commercial 48V 10Ah LiFePO4 battery pack is chosen as the ESS, and

Table 4.10: Information to calculate the power and the energy consumption

Motor efficiency (η)	75%
Mass factor (m)	220kg
Gravity acceleration (g)	9.81 m/s^2
Rolling resistance coefficient (C_{rr})	0.03
Air density (ρ)	1.2kg/ m^3
Drag coefficient (C_d)	0.7
Frontal area (A)	0.6 m^2

a BLDC HUB electric motor with 1000W, 48V and 35A with an internal controller as the PTS. These components are shown in Figure 4.13.

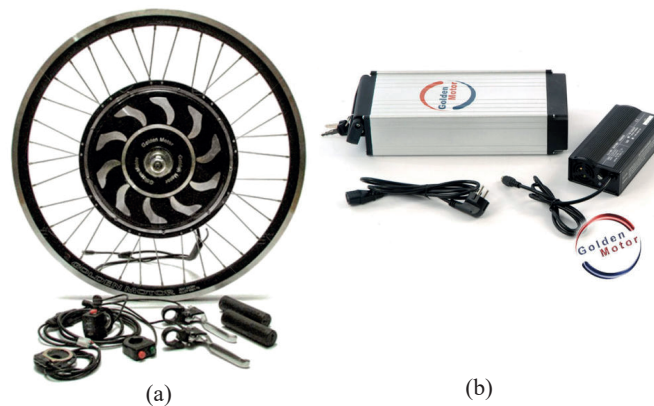


Figure 4.13: a) 1000W BLDC HUB motor b) 48V 10Ah LiFePO4 battery pack

After that, the original CAD modeling is modified, including the new components, as it is presented in Figure 4.14. For the assembly of the electric propulsion system, the lower shaft diameter of the front fork is increased to assemble a machined bushing that allows fitting the geometry of the motor shaft (See Appendix.A.0.3). For safety, two high-hold cone-point set screws per fork are implemented, and finally, another brake disc is installed to the motor frame and aligned with the front caliper. For the battery assembly, a sliding coupling bracket and a quick coupling power connector were introduced to remove the battery when charging, simulating a top case.

4.3.4 Domain-specific Design - Electronic engineering

A schematic design and a Printed Circuit Board (PCB) are proposed, using an Arduino Mega 2560 micro-controller, overvoltage protections, overcurrent protections, and a voltage converter as some of the main components. In addition, a LCD display 1602A and a hybrid/ICE select mode button

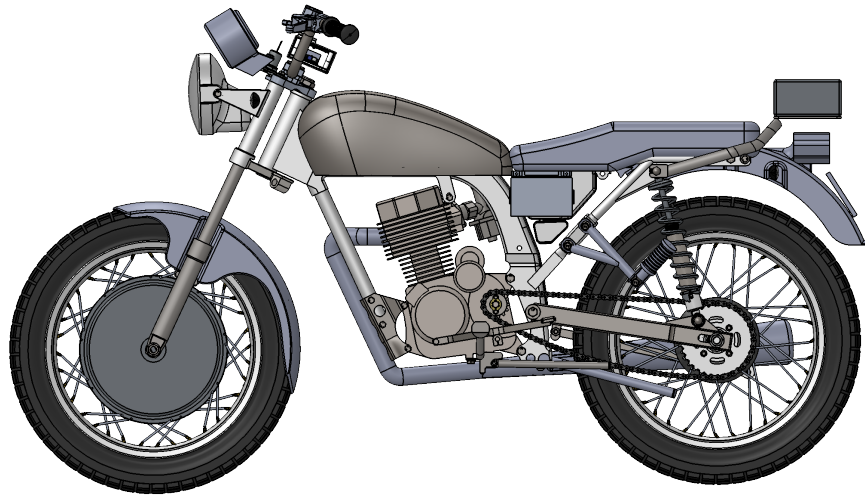


Figure 4.14: Case of Study 1 - CAD model

were included as the user interface; and a dual throttle design (electronic-mechanic) is proposed to maintain the user experience and the functionality of the motorcycle.

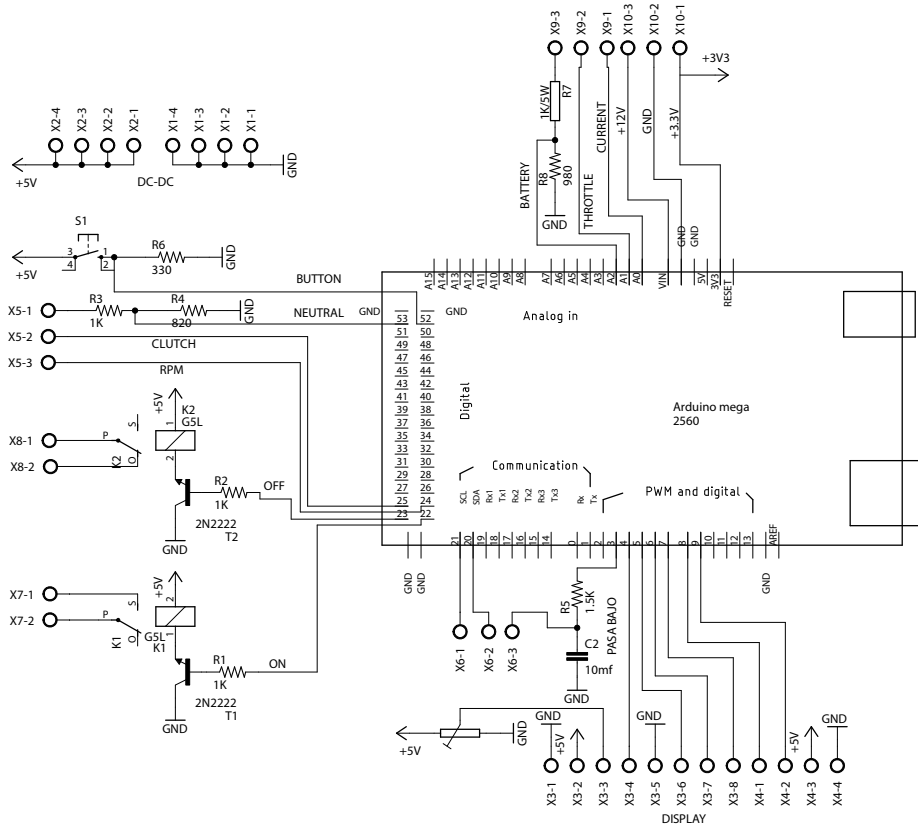


Figure 4.15: Electronic schematic design for Case of Study 1

The electrical system of the conversion kit is developed as independent wiring, for the purpose of intervening as little as possible the original motorcycle wiring. All the electronic system is mounted into an IP-51 plastic box installed on the handlebar using vehicular connectors in order to keep modularity, as it is presented in the Figure 4.16. All the electrical components, excluding the BLDC electric motor, are connected to the 12V 6.5Ah gel-cell motorcycle battery, and, therefore, to the ICE alternator.



Figure 4.16: Electronic box for Case of Study 1

4.3.5 Domain-specific Design - Information technology

To link the electric kit with the motorcycle, a system is developed based on a Finite-State Machine (FSM) presented in Figure 4.17. The control includes a battery SOC calculated with the equation 4.2, taken of the methodology proposed by Asaei and Habibidoost (2013) and three different driving modes: Hybrid mode, ICE mode, and Regenerative braking mode.

$$SOC = SOC_0 + \Delta Q / C_{battery} \quad (4.2)$$

$$\Delta Q = \int i \cdot dt$$

Where, SOC_0 is the initial SOC, ΔQ is the change in the battery pack charge, $C_{battery}$ is the capacity of the battery pack, and, i is the current of the batteries.

- *Hybrid mode*: Taking into account that the motorcycle has a manual transmission, user interaction is used as an actuator in a specific state of the logic control of the FSM to change the

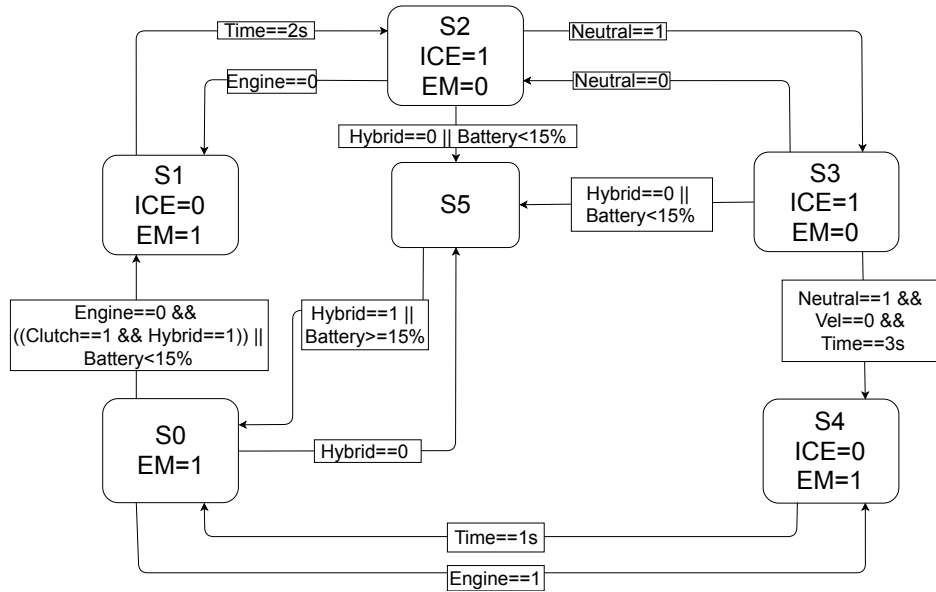


Figure 4.17: Finite-State Machine (FSM) for Case of Study 1

power source during the driving cycle. The control system identifies the neutral gear signal and enables the electric motor to be the only propulsion source. When the user feels the necessity to change the gearbox relation, (s)he operates the clutch, and the micro-controller receives a signal, which in turn starts the ICE system. During a driving cycle in urban areas, the vehicle makes frequent stops due to traffic and road signs, and as a result, the CS identifies the vehicle stop, and changes the propulsion source. Some extra functions, as low-battery, velocity, inclination, and engine ON/OFF signals, are being taken into account to improve the power source and identify the state of the engine, respectively.

- *ICE mode*: The motorcycle works only in the ICE mode as a conventional motorcycle when the user selects ICE mode or when the battery level is low during the hybrid mode.
- *Regenerative braking mode*: Brake sensors of the motorcycle (front and rear wheel) are connected directly to the electric motor controller, enabling the regenerative mode, independently of the two modes mentioned above.

4.3.6 Domain-specific Design - Motorcycle characterization

In order to validate the front architecture, the characterization of the motorcycle is carried out through a comparative development of the static, dynamic, and stability analyses.

4.3.6.1 Static analysis

In this analysis, the CADs of the original model and of the case of study 1 are compared, as it is observed in Table. 4.11. The results show that the proposed architecture respects the established ranges for almost all the parameters. Only the load distribution under static conditions shows an offset by 1% comparing with the literature information.

Table 4.11: Center of gravity, trail & weight comparison

	Original CAD	CASE 1 CAD
Wheel base (b)	1.254m	1.254m
Longitudinal position of the center of gravity (b)	0.55m	0.53m
Height of center of gravity (h)	0.49m	0.51m
Front weight (W_f)	42.4Kg	47.2Kg
Rear weight (W_r)	54.2Kg	63.9Kg
Total weight (W_r)	96.6Kg	111.1Kg
Load distribution (<i>rear-front</i>)	56%-44%	57.5%-42.5%
Normal trail (a_n)	0.08m	0.08m
Normal rear trail (b_n)	1.2m	1.2m
Trail ratio (R_n)	5.47%	5.18%

For this reason, it is possible to conclude that the architecture satisfies the static analysis. The geometry of the motorcycle has not been modified, that is why the weight distribution is the only variation. With an upward and backward movement of the center of mass, the motorcycle tends to understeer, the front wheel tends to slip in acceleration, and the rear wheel may lift in braking. However, the movement for this case is only 2 cm and it is not considered an alarming variation

4.3.6.2 Dynamic analysis

The critical scenarios of maximum traction and maximum acceleration are performed comparatively. In this case, the results show an increase due to weight variation; however, it does not reach the values of the maximum due to original motorcycle characteristics and minimum variations of the parameters. The motorbike with the electric kit does not have the necessary traction or acceleration to generate unstable conditions such as a wheelie, as it is shown in Tables 4.12 & 4.13.

4.3.6.3 Stability analysis

In this analysis calculations for wobble and Weave modes are carried out for the same speed ranges (0-100Km/h). In both methods, the frequency for the damped system rises as the speed increases,

Parameter		Original CAD	Case 1 CAD	Unit
$S = \frac{wp + whC_r - mg(p - b)}{h}$	s	1087.10	1172.74	<i>N</i>
$a = \frac{mg(p - (p - b)) - F_D h}{mh}$	a	11.06	10.35	<i>m/s²</i>
$N_r = \frac{mah + mg(p - b) + F_D h}{p}$	Nr	947.83	1090.57	<i>N</i>
$S = \mu_s * N_r$	Smax	758.27	872.46	<i>N</i>

Table 4.12: Case of study 1. ASSUMPTION 1 - Wheelie ($N_f = 0, N_r = w$)

Parameter		Original CAD	Case 1 CAD	Unit
$N_r = \frac{mg(p - b) - C_r wh}{p - \mu_s h}$	Nr	761.87	912.02	<i>N</i>
$a = \frac{(\mu_s * N_r) - C_r w - F_D}{m}$	a	6.11	6.37	<i>m/s²</i>
$N_f = mg * N_r$	Nf	185.86	178.45	<i>N</i>
$S = \mu_s * N_r$	S	609.50	729.61	<i>N</i>

Table 4.13: Case of study 1. ASSUMPTION 2 - Maximum traction ($S = \mu_s * N_r$)

and the damping ratio decreases, which represents a normal behavior. This is presented in Figure 4.18.

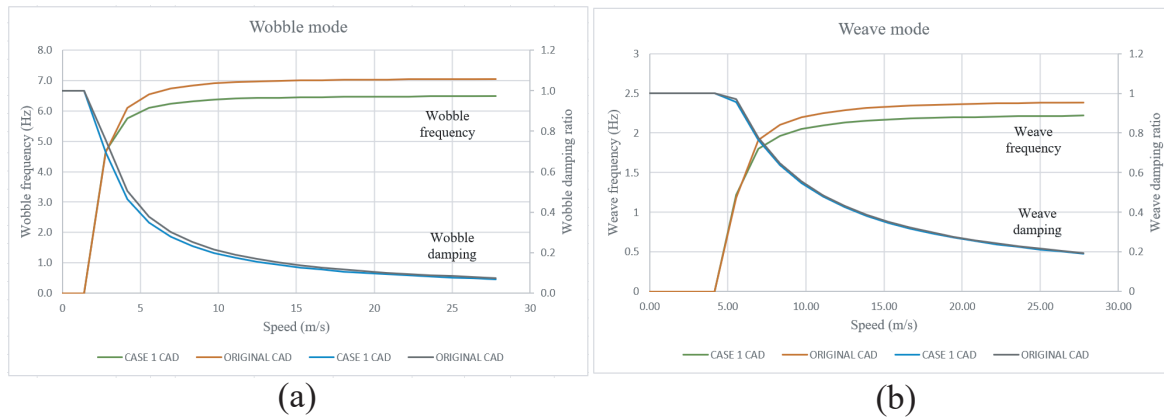


Figure 4.18: Case of study 1. a) Wobble mode b) Weave mode

In a comparison of the calculations between the original CAD with this architecture, the frequency

range for both modes decreases because both assemblies (front and rear) have an increase in weight and hence, inertia concerning the steering axis. In the wobble mode, the front assembly weight increase in a 33%, generating a 18% increase in the front assembly inertia and a 8% decrease in frequency. In the weave mode, the rear assembly weight increase in a 11% generating a 23% increase in the rear assembly inertia and a 7% decrease in frequency.

The Wobble frequency values remain between 4.68 - 6.49 Hz, while in weave frequency they remain between 1.22 - 2.22Hz, as it is presented in Table 4.14. The results fall in the normal ranges, that is why it can be concluded that the electric kit does not affect motorcycle stability and is viable to continue with a validation and integration process to fulfill the redesign method of the product.

Damping ratio	V(Km/h)	V(m/s)	ζ	v
$\zeta = \frac{cV + K_{\lambda f} a_n^2}{2V\sqrt{I_{\lambda f} K_{\lambda f} a_n \cos \varepsilon}}$	0	0	—	—
	5	1.39	—	—
	10	2.78	0.70	4.68
Frequency for the damped system	15	4.17	0.46	5.76
$v = \frac{1}{2\pi} \sqrt{\frac{K_{\lambda f} a_n}{I_{\lambda f}} \cos \varepsilon \sqrt{(1 - \zeta^2)}}$	20	5.56	0.35	6.10
	25	6.94	0.28	6.25
	30	8.33	0.23	6.33
Front assembly moment of inertia around the steering axis	35	9.72	0.20	6.37
	40	11.11	0.17	6.40
$I_{\lambda f} = I_{g f} + M_f * B_f^2$	45	12.50	0.15	6.43
Typical frequency values range from 4 Hz for heavy motorcycles to 10 Hz for lightweight motorcycles.	50	13.89	0.14	6.44
	55	15.28	0.13	6.45
	60	16.67	0.12	6.46
	65	18.06	0.11	6.47
	70	19.44	0.10	6.47
	75	20.83	0.09	6.48
	80	22.22	0.09	6.48
	85	23.61	0.08	6.48
	90	25.00	0.08	6.48
	95	26.39	0.07	6.49
100	27.78	0.07	6.49	

(a)

Damping ratio	V(Km/h)	V(m/s)	ζ	v
$\zeta = \frac{cV + K_{\lambda r} l^2}{2V\sqrt{I_{\lambda r} K_{\lambda r} l \cos \varepsilon}}$	0	0.00	—	—
	5	1.39	—	—
	10	2.78	—	—
Frequency for the damped system	15	4.17	—	—
$v = \frac{1}{2\pi} \sqrt{\frac{K_{\lambda r} l}{I_{\lambda r}} \cos \varepsilon \sqrt{(1 - \zeta^2)}}$	20	5.56	0.96	1.22
	25	6.94	0.76	1.80
	30	8.33	0.64	1.97
Rear assembly moment of inertia around the steering axis	35	9.72	0.55	2.05
	40	11.11	0.48	2.10
$I_{\lambda r} = I_{g r} + M_r * l^2$	45	12.50	0.42	2.13
The natural frequency of this side-to-side motion is zero when the forward speed is also zero and ranges from 0 to 4 Hz at high speed.	50	13.89	0.38	2.15
	55	15.28	0.35	2.17
	60	16.67	0.32	2.18
	65	18.06	0.29	2.19
	70	19.44	0.27	2.20
	75	20.83	0.25	2.20
	80	22.22	0.24	2.21
	85	23.61	0.22	2.21
	90	25.00	0.21	2.21
	95	26.39	0.20	2.22
100	27.78	0.19	2.22	

(b)

Table 4.14: Case of Study 1. a) Wobble mode b) Weave mode

4.3.7 System Integration

All systems designed and manufactured previously are validated and integrated into the motorcycle. The electric motor is assembled in the front wheel with minor fork tubes modifications, and a LiFePO4, 48V, 10Ah battery pack is installed in the back rack. Furthermore, the proposed control, the operating modes, and the user interface work correctly, as well as the electronic system that includes a plastic box with all the interfaces, the product wiring, and throttle with two functions, as it is shown in Fig.4.19.

In a driving cycle of 1140 seconds, 6.1 Km, 24 km/h average speed, and 1511 m.a.l.s in Medellín, Colombia, the electric kit worked around 35% of the total cycle reducing the emissions of Carbon



Figure 4.19: Motorcycle integration for Case of Study 1

Monoxide (CO) and Hydrocabons (HC). The cycle that presented traffic conditions in rush hours with obligatory stops helps to develop a functional prototype suitable for the context.

The redesign method outlined the necessary steps to perform a correct process and link in specific stages, calculations, and analysis. The obtained result is a functional prototype cataloged at level four in the Technology Readiness Levels (TRL) scale for estimating maturity. However, from the redesign process, it is possible to identify aspects complicating the replicability of the kit. On the one hand, the engine assembly on the front wheel requires a disassembly process of the suspension since it has a rigid axle. Therefore, a simple tire change process becomes a complicated task. On the other hand, it is necessary to strengthen the control, making the interaction of the electric kit autonomous in several stages of the driving cycle and not only in the range established in this case study.

Finally, the knowledge obtained in the development of the first case study will be the starting point to develop a second case study, turning the methodology into an iterative loop until getting a product suitable for the market.

4.4 Case of Study 2

4.4.1 System Design - Conceptual Design Phase

For the second case of study, the primary function of the product was established as “transform electric energy into mechanical energy”, the same as the case of study 1, since both products target the same overall objective. In this case, the inputs flows are also related to ICE motorcycle information, the environmental/human factors, and the energy/force flow produced in the process, while the outputs are directly related to the electric hybridization kit. A total of seven inputs (two energy/force flows and five information flows) and four outputs (three energy/force flows and one information flow) were identified, as it is shown in Figure 4.20.

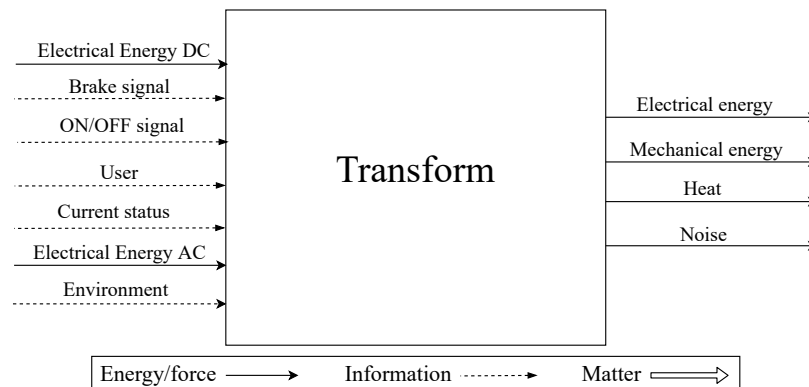


Figure 4.20: Black box for Case of Study 2

After that, a functional structure is proposed and presented in the Figure 4.21. From the conclusions obtained in the previous process, the input information decreases, which makes the interaction between the different flows easier. A total of 13 sub-functions are identified through which a rough product operation and the relationship that the conversion kit has with the motorcycle components are analyzed.

Subsequently, a morphological process is developed, finding a little less than 140.000 concepts that need to be synthesized through the screening process that is performed with the CRs as filters. The results are eight concepts, as it is shown in Appendix A.0.4.

- CR5 - The kit must be affordable.
- CR4 - The kit must be minimally invasive.
- CR7 - The kit must be easy to assemble and disassembly
- CR12 - The kit must keep the motorcycle driving ease

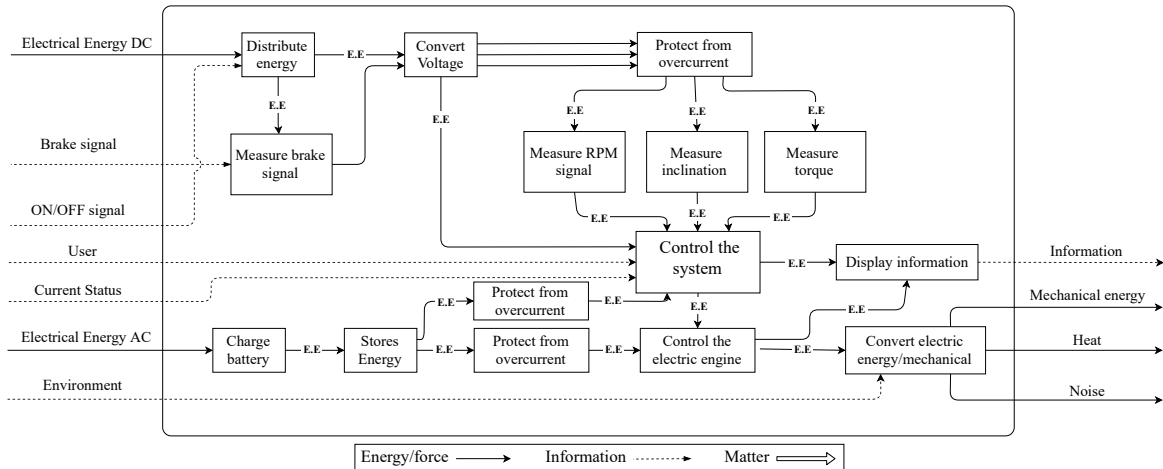


Figure 4.21: Functional Structure for Case of Study 2

With the result, the final step is the concept-scoring matrix presented in the Table 4.15, and the results show the solution concept two as the best option. However, the concept one obtained a high score so that it will be analyzed in the process.

Selection Criteria	Weight	Concept															
		1		2		3		4		5		6		7		8	
		Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
The kit must be affordable	17%	4	0.68	3	0.51	3	0.51	2	0.34	5	0.85	3	0.51	5	0.85	4	0.68
The kit must be minimally invasive	20%	5	1	5	1	5	1	5	1	4	0.8	4	0.8	4	0.8	4	0.8
The kit must be easy to assembly and disassembly	18%	5	0.9	5	0.9	4	0.72	4	0.72	4	0.72	4	0.72	4	0.72	4	0.72
The kit must have a long lifespan	30%	4	1.2	5	1.5	3	0.9	4	1.2	3	0.9	3	0.9	3	0.9	4	1.2
The kit must support water and dust	15%	4	0.6	4	0.6	4	0.6	4	0.6	3	0.45	3	0.45	3	0.45	3	0.45
Total Score		4.38		4.51		3.73		3.86		3.72		3.38		3.72		3.85	
Total Score Rank	100%	2		1		5		3		6		8		7		4	
Continue		-		Develop		-		-		-		-		-		-	

Table 4.15: Concept-scoring matrix for Case of Study 2

4.4.2 System Design - Embodiment Design Phase

As in case study one, a schematic diagram of the product is developed, including a chunks clustering, the concept solution, and energy/force flow specification, as it is presented in the Figure 4.22. The amount of sub-functions decreases considerably, which in turn reduces the degree of complexity in the interactions. The chunks are clustered in three groups: CS, ESS & PTS.

Subsequently, a rough geometric layout of the product is created to locate the principal groups in the motorcycle original architecture, as it is observed in Figure 4.23. The PTS, for this case, is located in the rear wheel for assembly facility, while the ESS and CS are located in the motorcycle back due to space constraints.

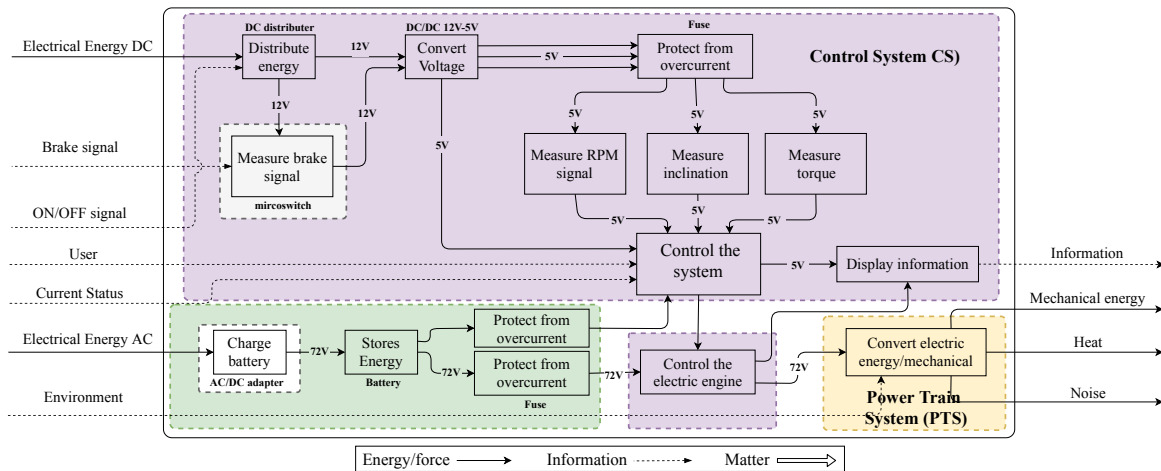


Figure 4.22: Schematic of the product for Case of Study 2

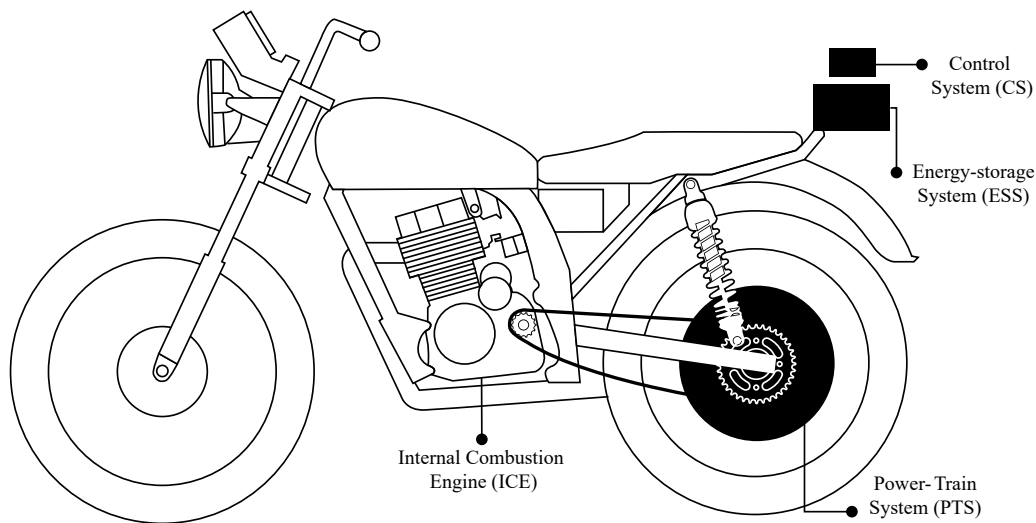


Figure 4.23: Architecture for Case of Study 2

4.4.3 Domain-specific Design - Mechanical engineering

From the components sizing, made with the local driving cycle, the constituent elements of the electric kit of the case study 2 are selected. Regarding the electric motor, it was decided to choose a BLDC HUB motor of 3000W 72V, with geometrical characteristics adaptable to the rear motorcycle assembly, as it is presented in the Figure 4.24.

Concerning the ESS and CS, a 72V 20Ah Li-ion battery pack and a Sabvoton 72150 controller were chosen, and they are shown in the Figure 4.25. Both components are selected to meet the current and voltage requirements of the electric motor for optimum performance. Those components have a greater capacity than the obtained in the sizing process, mainly due to the research process.



Figure 4.24: QS Motor 205 50H V3 Motor 3000W Electric High Power Bike Spoke Hub Motor

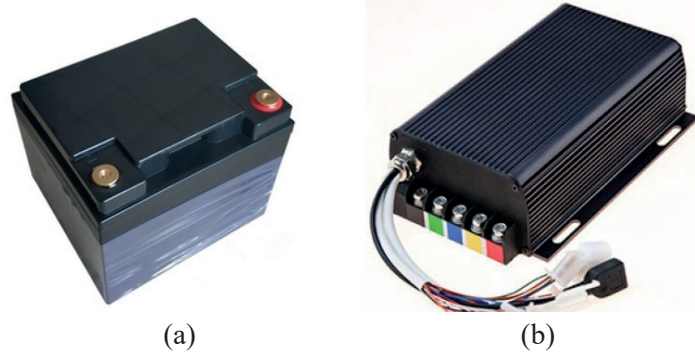


Figure 4.25: a) Li-ion battery pack, b) Sabvoton controller 72150

With the selected components, some modifications and mechanical adaptations were necessary for the assembly. On the one hand, due to the limitations space, the need to maintain the modularity, and the dimensions of the components, the ESS and CS were located at the rear of the motorcycle designing a top-case to storage the parts without motorcycle modifications, as it is observed in the Figure 4.26.

On the other hand, the engine was installed in a 17" rim, including a disc brake kit, in order to facilitate the assembly, disassembly, and maintenance process. For this adaptation, a cut is made on the back of both sides of the swingarm, followed by a hole in the right part to assemble the plate that holds the disc brake, as it is shown in the Figure 4.27a). The loads to which the piece is subjected are calculated and simulated through ANSYS verifying that the modifications would not affect the structurality of the motorcycle. The results of the analysis are presented in the Figure 4.27c).

Subsequently, the electric motor case is modified. The left cap is removed, and a new cap is developed to link the chain drive of the combustion engine with the rear tire (See Appendix. A.0.5). This process uses CAD modeling, ANSYS analysis under static and dynamic loads, and 3D printed prototypes to validate and optimize the design, as it is shown in Figure 4.28.

At this point, the adaptations make it possible to assemble the three constituent systems of the electric kit. However, it is necessary to develop additional parts to tighten the chain and support the

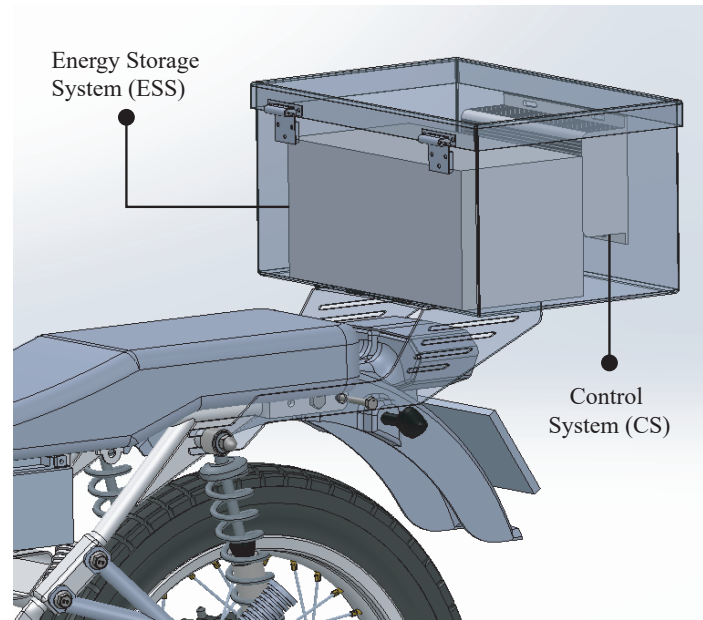


Figure 4.26: Top-Case design for Case of Study 2

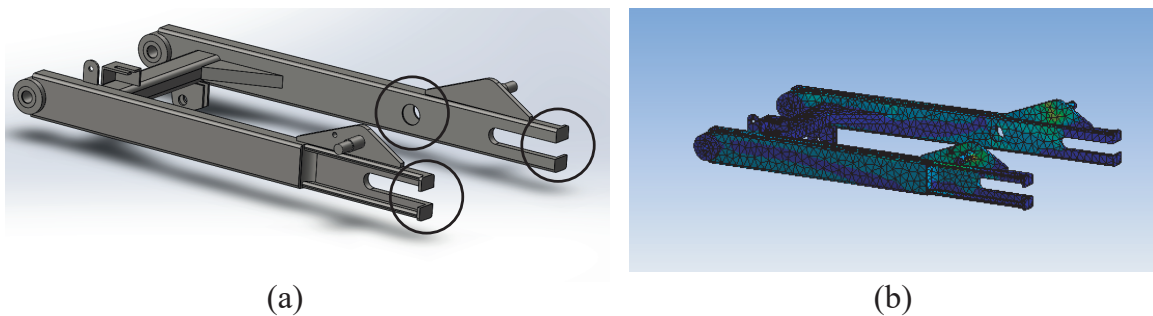


Figure 4.27: Swing-arm modifications for Case of Study 2

new disc brake system. On the one hand, the chain tensor system consists of 4 easily manufactured parts that also allow the wheel to be aligned and prevent rotation of the motor shaft through a simple assembly, as it is shown in the Figure 4.29. For more information refers the Appendix A.0.6.

On the other hand, a plate is developed to support the brake pump and a drive mechanism adapted to the original brake lever. The components are easily assembled to the existing attachment points on the motorcycle, and the system is linked to the brake kit purchased with the engine, as it is shown in the Figure 4.30.

The result obtained in the process of mechanical development presents a low level of intervention on the motorcycle. Therefore, it is decided to consolidate the modifications in a CAD model, as it is shown in the Figure 4.31, and to start with the process of the detailed design of the other constituent systems of the product.

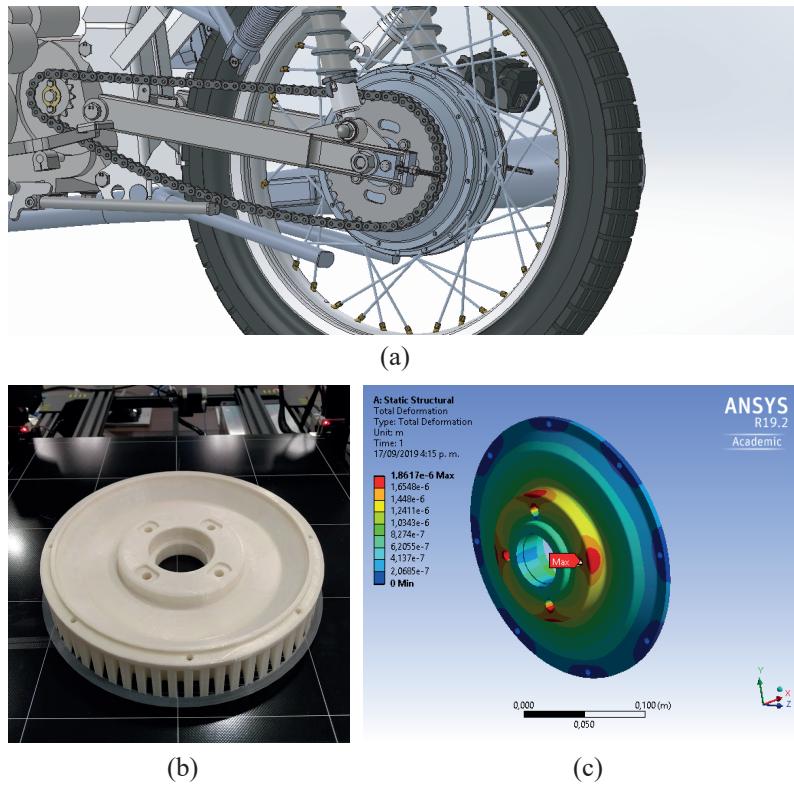


Figure 4.28: Case of Study 2. a) CAD design b) 3D prototype c) ANSYS analysis

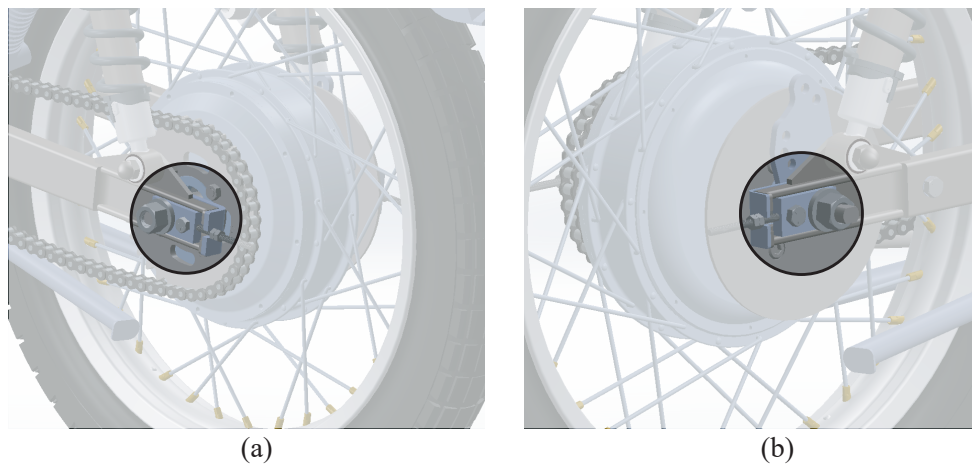


Figure 4.29: Chain adjusters for Case of Study 2

4.4.4 Domain-specific Design - Electronic engineering

For the development of the electronic system, a nominal voltage of 72v is selected due to the standardization of this value in available electric motorcycles. The SABVOTON controller is responsible

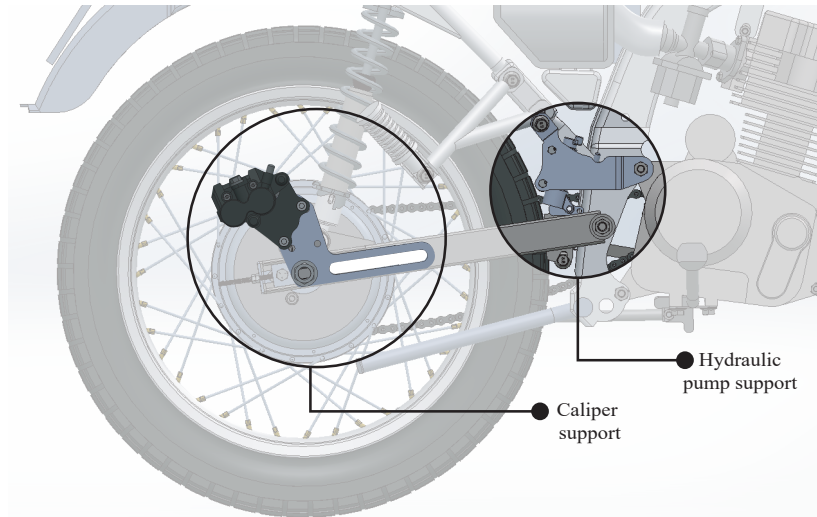


Figure 4.30: Motorcycle brake system for Case of Study 2

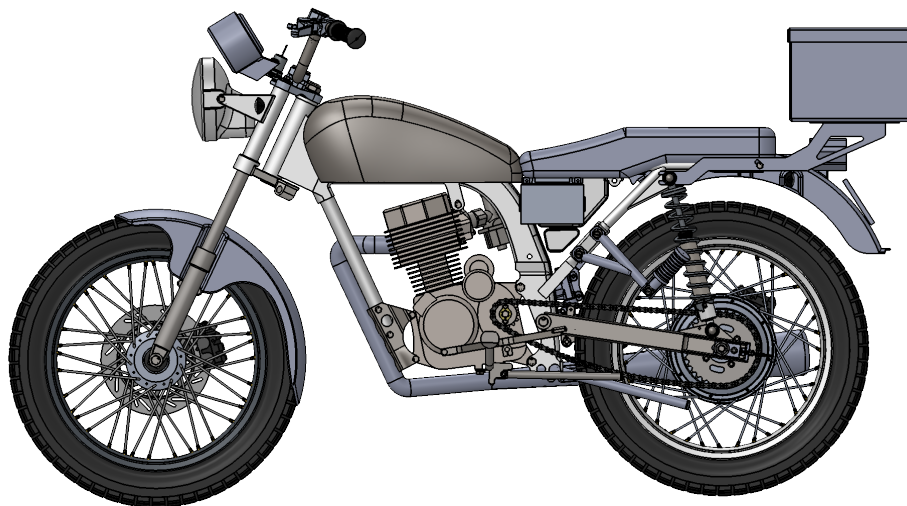


Figure 4.31: Case of Study 2 - CAD model

for distributing the motor current, and managing the state of charge of the battery, the performance of the system and the signals from the actuators/sensors constituents of the hybridization kit. Also, a 72V to 12V DC-DC converter is integrated to adapt the peripheral components and it is assembled in the top-case to keep the electrical components in the same place.

On the other hand, vehicular connectors are used to facilitate the modularity of the product. Both the battery and the HUB motor include quick coupling connectors, which are assembled directly to the controller. And this, in turn, has the necessary inputs to link the signals of the throttle, regenerative brake, cruiser mode and reverse mode (See Appendix. A.0.7).

Finally, it is necessary to acquire motorcycle signals; therefore, information is obtained from the

gear sensor, ICE engine, start switch, the front/rear brake signal, spark plug cable, among others. These actuators and sensors would deliver information to the controller, which in turn would guide the electric motor controller and the operation of the kit.

4.4.5 Domain-specific Design - Information technology

The control system designed for this case study seeks to automate the operation of the electric kit and to improve the user experience. A parallel hybrid architecture is proposed, where both sources of propulsion intervene in the traction of the vehicle. For this, the operation must be similar to car functionality, where the electrical system becomes a support to the combustion engine. In this case, the CS permanently analyzes signals from the environment, the motorcycle, and the kit battery determining when to include and exclude the HUB engine.

A control with two-level is suggested; in the upper one, the unit is in charge of deciding according to the actuators/sensors of the kit, and in the lower one, the electric motor controller is in charge of sending commands to activate and deactivate the electric motor. Two alternatives of interaction flows are presented in the Figure 4.32 as continuous and dotted lines.

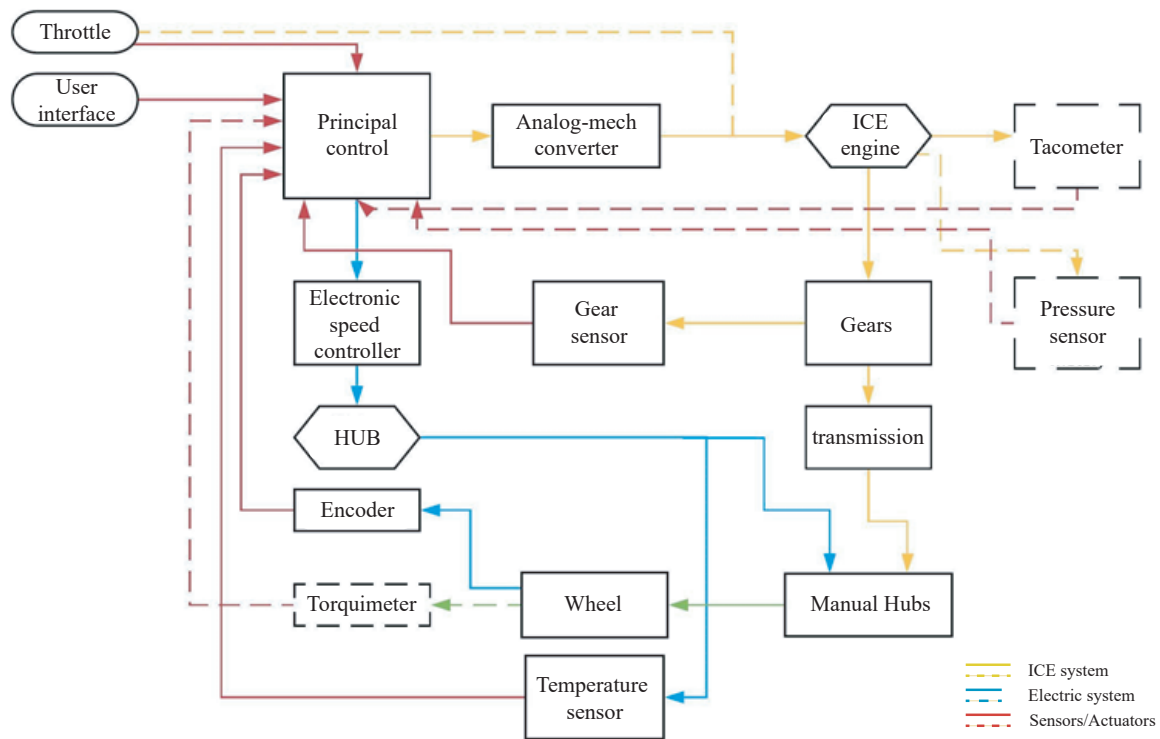


Figure 4.32: Case of Study 2 - Control System

4.4.6 Domain-specific Design - Motorcycle characterization

For architecture validation, a second motorcycle characterization is carried out, focused on static, dynamic, and stability analyzes.

4.4.6.1 Static analysis

In this analysis, the original model is compared with the two cases of study, as it is shown in Table. 4.16.

Table 4.16: Center of gravity, trail & weight comparison

	Original CAD	CASE 1 CAD	CASE 2 CAD
Wheel base (p)	1.254m	1.254m	1.233m
Longitudinal position of the center of gravity (b)	0.55m	0.53m	0.35m
Height of center of gravity (h)	0.49m	0.51m	0.53m
Front weight (W_f)	41.8Kg	46.4Kg	36.9Kg
Rear weight (W_r)	54.8Kg	64.5Kg	93.6Kg
Total weight (W_r)	96.6Kg	111.2Kg	130.5Kg
Load distribution (<i>rear-front</i>)	57%-43%	58%-42%	72%-28%
Normal trail (a_n)	0.08m	0.08m	0.08m
Normal rear trail (b_n)	1.22m	1.22m	1.18m
Trail ratio (R_n)	5.29%	4.98%	2.81%

The results show that the proposed architecture is between the established ranges for almost all the parameters. However, the load distribution under static conditions shows an offset by 14% and 15% comparing CASE 2 with CASE 1 and the original CAD, respectively. The additional weight was placed on the back of the motorcycle, therefore, the variation of the weight for the architecture 2 generates an upward and backward movement of the center of mass. The height rises 4cm compared to the original CAD, while the longitudinal position of the center of mass moves back 2cm. However, the movement for both cases is minimum and remains within the acceptable ranges, considered a not alarming variation and the movement could be analyzed as a weight generated by a passenger, or in this case, a top-case.

Finally, the trail ratio is 1% below the average range, since the mechanical modifications made decrease the wheelbase around 20mm. However, the value of the wheelbase is within the chain tension range.

4.4.6.2 Dynamic analysis

The critical scenarios of maximum traction and wheelie are performed comparatively between the original CAD versus both cases of study. Results show that, due to the weight distribution, the CASE 2, in contradistinction to both the original CAD and the CASE 1, has the necessary torque to induce the wheelie condition. Therefore, CASE 2 fulfills the assumption 1 and does not fulfill the assumption 2 since the maximum traction could not be employed. Results for both assumptions are presented in Tables 4.17 & 4.18.

<i>Parameter</i>		<i>Original CAD</i>	<i>Case 1 CAD</i>	<i>Case 2 CAD</i>	<i>Unit</i>
$S = \frac{wp + whC_r - mg(p - b)}{h}$	<i>s</i>	1087.10	1172.74	875.14	<i>N</i>
$a = \frac{mg(p - (p - b)) - F_D h}{mh}$	<i>a</i>	11.06	10.35	6.51	<i>m/s2</i>
$N_r = \frac{mah + mg(p - b) + F_D h}{p}$	<i>Nr</i>	947.83	1090.57	1280.47	<i>N</i>
$S = \mu_s * N_r$	<i>Smax</i>	758.27	872.46	1024.38	<i>N</i>

Table 4.17: Case of Study 2. ASSUMPTION 1 - Wheelie ($N_f = 0, N_r = w$)

<i>Parameter</i>		<i>Original CAD</i>	<i>Case 1 CAD</i>	<i>Case 2 CAD</i>	<i>Unit</i>
$N_r = \frac{mg(p - b) - C_r wh}{p - \mu_s h}$	<i>Nr</i>	761.87	912.02	N/A	<i>N</i>
$a = \frac{(\mu_s * N_r) - C_r w - F_D}{m}$	<i>a</i>	6.11	6.37	N/A	<i>m/s2</i>
$N_f = mg * N$	<i>Nf</i>	185.86	178.45	N/A	<i>N</i>
$S = \mu_s * N_r$	<i>S</i>	609.50	729.61	N/A	<i>N</i>

Table 4.18: Case of Study 2. ASSUMPTION 2 - Maximum traction ($S = \mu_s * N_r$)

4.4.6.3 Stability analysis

For the second architecture, the analysis of the Wobble and Weave modes is developed in a comparative way, including the original CAD and architecture one, as it is presented in the Figure 4.33.

The results for the original motorcycle and the two case studies show typical behavior. While speed increases, the frequencies increase, and damping decreases, both trying to stabilize. Comparing calculations of the second architecture with the original one, the frequency range for wobble mode is the same since the weight and inertia concerning the steering axis of the frontal assembly were not modified. For the weave mode, the rear assembly weight increases in 43%, generating a 96% increase in inertia, and therefore, a 26% decrease in frequency.

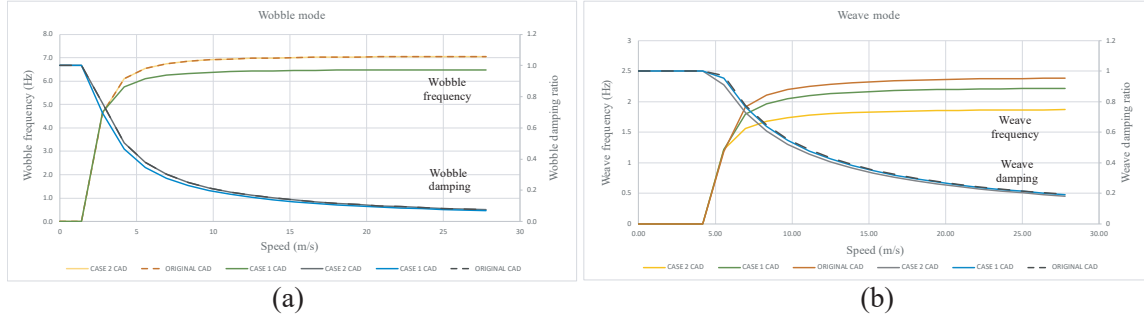


Figure 4.33: Case of Study 2. a) Wobble mode b) weave mode

The Wobble frequency values are between 4.63 - 7.05 Hz, while the weave frequency values are between 1.21 - 1.87 Hz, as it is observed in the Table 4.19. The results remain in the normal ranges, that is why it can be concluded that the electric kit does not affect motorcycle stability, and it is viable to continue with a validation and integration process to fulfill the re-design method of the product.

Damping ratio	V(Km/h)	V(m/s)	ζ	ν
$\zeta = \frac{cV + K_{\lambda f} a_n^2}{2V\sqrt{I_{Af} K_{\lambda f} a_n \cos \epsilon}}$	0	0	—	—
	5	1.39	—	—
	10	2.78	0.76	4.63
Frequency for the damped system	15	4.17	0.50	6.11
$\nu = \frac{1}{2\pi} \sqrt{\frac{K_{\lambda f} a_n}{I_{Af}} \cos \epsilon \sqrt{1 - \zeta^2}}$	20	5.56	0.38	6.55
	25	6.94	0.30	6.74
	30	8.33	0.25	6.85
	35	9.72	0.22	6.91
Front assembly moment of inertia around the steering axis	40	11.11	0.19	6.95
	45	12.50	0.17	6.97
$I_{Af} = I_{gf} + M_f * B_f^2$ Typical frequency values range from 4 Hz for heavy motorcycles to 10 Hz for lightweight motorcycles.	50	13.89	0.15	6.99
	55	15.28	0.14	7.01
	60	16.67	0.13	7.02
	65	18.06	0.12	7.03
	70	19.44	0.11	7.03
	75	20.83	0.10	7.04
	80	22.22	0.09	7.04
	85	23.61	0.09	7.05
	90	25.00	0.08	7.05
	95	26.39	0.08	7.05
	100	27.78	0.08	7.05

(a)

Damping ratio	V(Km/h)	V(m/s)	ζ	ν
$\zeta = \frac{cV + K_{\lambda r} l^2}{2V\sqrt{I_{Ar} K_{\lambda r} l \cos \epsilon}}$	0	0.00	—	—
	5	1.39	—	—
	10	2.78	—	—
Frequency for the damped system	15	4.17	—	—
$\nu = \frac{1}{2\pi} \sqrt{\frac{K_{\lambda r} l}{I_{Ar}} \cos \epsilon \sqrt{1 - \zeta^2}}$	20	5.56	0.91	1.21
	25	6.94	0.73	1.56
	30	8.33	0.61	1.68
	35	9.72	0.52	1.74
Rear assembly moment of inertia around the steering axis	40	11.11	0.46	1.78
	45	12.50	0.40	1.80
$I_{Ar} = I_{gr} + M_r * l^2$ The natural frequency of this side-to-side motion is zero when the forward speed is also zero and ranges from 0 to 4 Hz at high speed.	50	13.89	0.36	1.82
	55	15.28	0.33	1.83
	60	16.67	0.30	1.84
	65	18.06	0.28	1.85
	70	19.44	0.26	1.85
	75	20.83	0.24	1.86
	80	22.22	0.23	1.86
	85	23.61	0.21	1.86
	90	25.00	0.20	1.86
	95	26.39	0.19	1.87
	100	27.78	0.18	1.87

(b)

Table 4.19: Case of Study 2. a) Wobble mode b) Weave mode

4.4.7 System Integration

All systems designed and manufactured previously are validated and integrated into the motorcycle. The electric motor is assembled on the rear tire through minimal modifications to the swingarm, and some assembly components development. On the other hand, the battery (Li-ion 72V-20Ah), the controller (Sabvoton 72150), and additional electronic components were located in a top-case designed

to minimize the motorcycle intervention degree, and to improve modularity by placing the elements of higher volume in the same place.

The methodology stages allowed to address in an organized way the different development process challenges to finally obtain a functional prototype at level four in the TRL method for estimating the maturity, as it is shown in the Figure 4.34. The installation of the electric kit modifies the motorcycle weight distribution; however, they keep within the ranges established in the literature for the evaluated parameters.

Finally, it is possible to conclude that the kit does not affect the vehicle dynamic stability, meeting the initial design requirements, and allowing the integration of electrical technologies in combustion motorcycles. The knowledge obtained in the development of the second case study would be the starting point to develop other iterations, turning the methodology into a loop until getting a product suitable for the market.

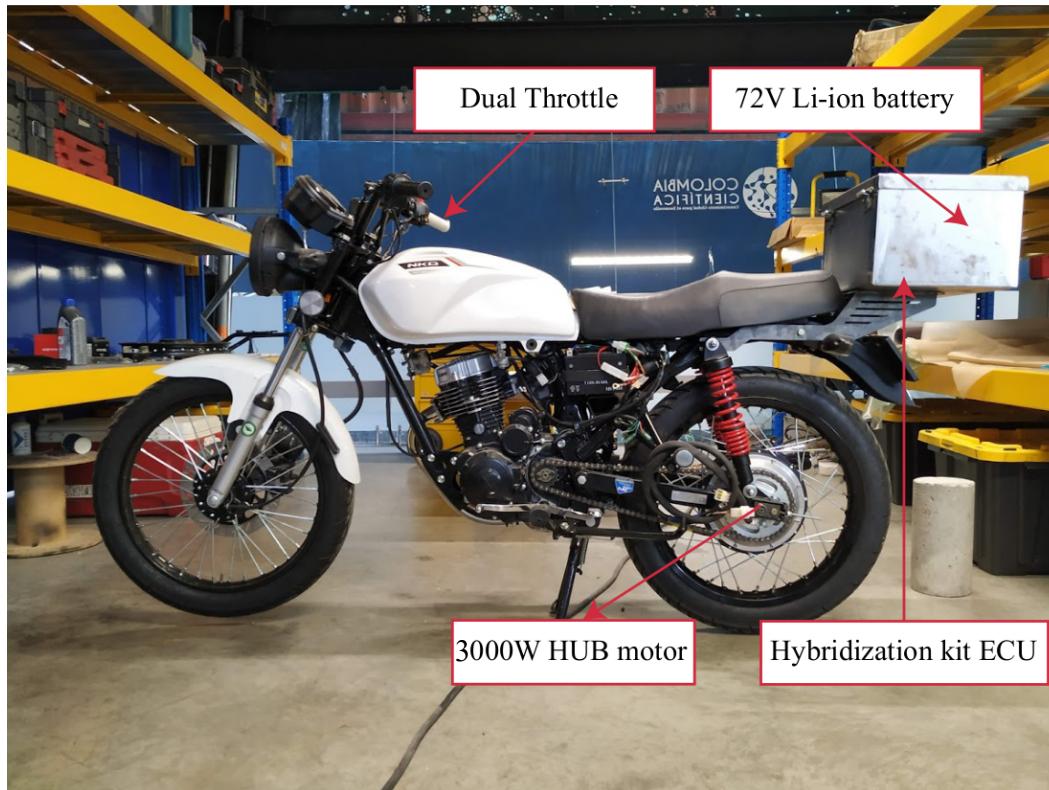


Figure 4.34: Motorcycle integration for Case of Study 2

Chapter 5

Conclusions

The dynamic analysis method applied in the VDI 2206 methodology helped designers to understand how the location of the component of an electric kit for motorcycle hybridization affected the stability of a motorcycle NKD 125c.c of the AKT Motos company. The tool, applied in two specific stages of the methodology, allowed designers to consider dynamic variables previously to the redesign process and to make decisions about the new components and necessary modifications. On the one hand, it was introduced in the early stages to obtain relevant technical information through a reverse engineering process. On the other hand, it was introduced in detail design stages, to comparatively evaluate the stability when modifying the motorcycle and correcting errors before the production process.

VDI guideline 2206, considered as a standard, offers a step-by-step approach for the specific development of products involving different engineering domains. For this case of motorcycle redesign, the general structure of the methodology sought to guide the designer through the different fundamental stages of the process, starting with the collection of technical and design information, followed by a conceptual design process, and finally stages corresponding to detailed design, manufacturing, and testing. Involving dynamic analysis tools of stability variables had not been done before for the motorcycle redesign process. So the method contributed to systematically develop two functional architectures, with level four of the maturity TRL scale, which met the requirements set by users and the modularity parameters that characterize this type of product.

From the results obtained, it is possible to define that the two developments of the hybridization kits are stable and conclude that placing the weight unevenly along the motorcycle generates handling problems that would put the driver at high risk. In case study 1, the evaluation of the static parameters showed a standard variation corresponding to the additional weight added by the kit. With a 15% increase of the weight, the load distribution and the location of the center of mass varied by only 1.5% and 4%, respectively, which means that the components located uniformly. As for the dynamic parameters, the critical cases to which the motorcycle was subjected showed that it does not have the

necessary acceleration to present a wheelie condition; therefore, the motorcycle can reach its maximum traction without generating unstable conditions. Finally, concerning the stability modes (Wobble and Weave), the increase in weight and inertia of the assemblies (rear and front) generated a decrease in the frequency of the modes. In the wobble mode, the frequency and damping ratio decreased by 8% and 5%, while in the weave mode, the frequency and damping ratio decreased by 7% and 1%, respectively. The results present the architecture within the normal ranges, so it can be concluded that the front electric kit does not affect the stability of the motorcycle.

In case study 2, the static parameters showed some irregularities due to a 35% increase in the weight of the rear end. Thus, the load distribution and the trail ratio varied by 15% and 1.2%, respectively, leaving the normal ranges and possibly generating conditions of instability. As for the dynamic analyses, the results showed a wheelie condition because the variations in weight produce the acceleration necessary for the tire to lift. Both the static and dynamic conditions showed that the additional weight, located mainly in the rear end, could have consequences on the safety of the driver; however, it is possible to analyze it as carrying the weight of a passenger permanently or a top case. Finally, concerning the stability modes, the wobble mode is not affected since there were no modifications in the front end, while the weave mode the frequency and the damping ratio decreased by 26% and 4%, respectively. Once again, as in the previous case, the results show the architecture within the normal ranges, being able to conclude that the rear electric kit does not affect the stability of the motorcycle.

The modifications made for both cases are technically feasible and comply with the stability analysis. The architecture presented in case study 1, obtained better results than case study 2; however, it did not meet some design requirements, and in field tests, the additional weight in the front end, generates maneuverability problems. On the other hand, the architecture in case study 2 presented some irregularities in the static and dynamic analyses but improved the modularity, the assembly process, and the maneuverability thanks to the unification of the electrical components in a top case. The rear architecture has a better performance and is the right way in the process of developing an electric kit for the hybridization of motorcycles for the Colombian context.

Finally, it is possible to conclude that the method implemented in the VDI 2206 methodology is a scientific contribution that helped the process of redesigning motorcycles by providing analyses and relevant information to determine the distribution with the least dynamic effect and which in turn would modify the originality of the vehicle to a lesser extent. As future work, an iterative process must continue in which the maturity is increased, and finally, it becomes a product for the market. On the other hand, it is essential to standardize components and assembly methods to other motorcycles, making it a general product, easy to install, and viable for a wide range of motorcycle models and brands. It is also important to compare through experimentation the results obtained theoretically.

For this purpose, the motorcycle could be instrumented in order to measure variables which would allow to validate the stability models generated for this study. Finally, based on the found solutions, an economic and legal validation process will be initiated to include these variables in the proposed methodology and to obtain a viable product for the Colombian context.

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Appendix A

Appendix Title

A.0.1 Morphological Chart & Solution Screening - Case of Study 1

Morphological Chart																	
Sub-function Solution Concepts																	
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Row #	Distribute energy	Convert voltage	Protect from overcurrent	Measure break signal	Measure neutral gear signal	Measure current signal	Measure throttle signal	Measure RPM signal	Select hybrid/ICE mode	Display information	Control the system	Allow the electric energy flow	Charge battery	Stores energy	Control electric engine	Convert electrical energy / information	Convert electric energy / mechanical
1	multi socket (1.1)	DC-DC (2.1)	Variable resistor (3.1)	pressure sensor (4.1)	Mikrowich (5.1)	Slunt resistor (6.1)	Servo motor (7.1)	Hall sensor (8.1)	key switch (9.1)	Speaker (10.1)	micro-controller (11.1)	Crimp terminals (12.1)	wind energy (13.1)	Battery (14.1)	PLC (15.1)	sensors (16.1)	electromagnetic generators (17.1)
2	DC-bus (1.2)	linear regulator (2.2)	Fuse (3.2)	Mikrowich (4.2)	contact sensor (5.2)	current sensor (6.2)	Potenciometer (7.2)	Infrared sensor (8.2)	Button (9.2)	Light-emitting diode (10.2)	PLC (11.2)	Connector strip (12.2)	solar energy (13.2)	pumping water (14.2)	micro-controller (15.2)	actuators (16.2)	
3	cable (1.3)		Dayunator (3.3)				Hall sensor (7.3)	Inductive sensor (8.3)	3 position selector switch (9.3)	Display LCD (10.3)	Analog systems (11.3)	Tin lead solder (12.3)	electric energy (13.3)	air compression (14.3)	Analog systems (15.3)		
4			Reed switch (3.4)									Relay circuit (12.4)		flywheel (14.4)			

Solutions screening - Parameter (The kit must be affordable)																	
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Row #	Distribute energy	Convert voltage	Protect from overcurrent	Measure break signal	Measure neutral gear signal	Measure current signal	Measure throttle signal	Measure RPM signal	Select hybrid/ICE mode	Display information	Control the system	Allow the electric energy flow	Charge battery	Stores energy	Control electric engine	Convert electrical energy / information	Convert electric energy / mechanical
1	3	3	5	3	5	3	0	5	3	3	5	5	0	5	0	5	5
2	3	5	5	5	3	5	3	3	5	5	0	5	0	0	5	3	
3	5		3				5	3	3	3	0	5	5	0	0		
4			3									5		0			

Solutions screening - Parameter (The kit must be minimally invasive)																	
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Row #	Distribute energy	Convert voltage	Protect from overcurrent	Measure break signal	Measure neutral gear signal	Measure current signal	Measure throttle signal	Measure RPM signal	Select hybrid/ICE mode	Display information	Control the system	Allow the electric energy flow	Charge battery	Stores energy	Control electric engine	Convert electrical energy / information	Convert electric energy / mechanical
1	0	3	5	3	5	0	0	5	0	0	5	5	0	5	0	5	5
2	3	5	5	5	3	5	0	3	5	5	0	5	0	0	5	3	
3	5		3				5	0	0	3	0	5	5	0	0		
4			3									5		0			

Solutions screening - Parameter (The kit must be easy to assembly and disassembly)																	
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Row #	Distribute energy	Convert voltage	Protect from overcurrent	Measure break signal	Measure neutral gear signal	Measure current signal	Measure throttle signal	Measure RPM signal	Select hybrid/ICE mode	Display information	Control the system	Allow the electric energy flow	Charge battery	Stores energy	Control electric engine	Convert electrical energy / information	Convert electric energy / mechanical
1	0	3	0	0	5	0	0	5	0	0	5	0	0	5	0	5	5
2	5	5	5	5	3	5	0	3	5	5	0	0	0	0	5	0	
3	0		0				5	0	0	3	0	0	5	0	0		
4			0									5		0			

Subproblem Solutions screening - Parameter (The kit must keep motorcycle driving easy)																	
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Row #	Distribute energy	Convert voltage	Protect from overcurrent	Measure break signal	Measure neutral gear signal	Measure current signal	Measure throttle signal	Measure RPM signal	Select hybrid/ICE mode	Display information	Control the system	Allow the electric energy flow	Charge battery	Stores energy	Control electric engine	Convert electrical energy / information	Convert electric energy / mechanical
1	0	3	0	0	5	0	0	5	0	0	5	0	0	5	0	5	5
2	5	5	5	5	3	5	0	3	5	0	0	0	0	0	5	0	
3	0		0				5	0	0	5	0	0	5	0	0		
4			0									5		0			

Table A.1: Morphological chart & Solutions screening - Case of Study 1

A.0.2 Driving cycle data-set

Table A.2: Driving Cycle Data Set

Time (min)	Time (seg)	Time (h)	δt	Speed (km/h)	Speed (m/s)	slope (%)	Distance (Km)	Distance interval(m)	Acceleration	Pos. Acceleration	Power (w)	Energy (wh)
1474.00	0	0.000	0.000	0	0.00	0	0	0	0	0	0.00	
1486.00	12	0.003	0.003	1.1	0.31	0.5	0.004	3.75	0.54	0.54	78.73	0.26
1492.00	18	0.005	0.002	10.2	2.83	0.7	0.022	17.96	0.42	0.42	653.11	1.09
1499.00	25	0.007	0.002	8.6	2.39	2.5	0.039	16.87	-0.06	0.00	333.14	0.65
1504.00	30	0.008	0.001	17.1	4.75	2.2	0.063	24.07	0.47	0.47	1369.24	1.90
1510.00	36	0.010	0.002	7.8	2.17	6.6	0.076	12.99	-0.43	0.00	324.67	0.54
1519.00	45	0.013	0.003	3.4	0.94	6.7	0.084	8.34	-0.14	0.00	225.52	0.56
1525.00	51	0.014	0.002	7.6	2.11	8.3	0.097	12.94	0.19	0.19	804.17	1.34
1532.00	58	0.016	0.002	18.7	5.19	0.5	0.132	35.48	0.44	0.44	1196.17	2.33
1537.00	63	0.018	0.001	49.7	13.81	-2.2	0.204	71.96	1.72	1.72	9056.24	12.58
1544.00	70	0.019	0.002	35.9	9.97	0.2	0.275	70.89	-0.55	0.00	-680.85	-1.32
1549.00	75	0.021	0.001	18.3	5.08	6.5	0.301	25.51	-0.98	0.00	-66.65	-0.09
1557.00	83	0.023	0.002	8.8	2.44	1.7	0.318	17.66	-0.33	0.00	95.45	0.21
1561.00	87	0.024	0.001	32.4	9.00	-0.5	0.361	42.69	1.64	1.64	5243.01	5.83
1567.00	93	0.026	0.002	43.6	12.11	2.2	0.432	71.09	0.52	0.52	3654.49	6.09
1575.00	101	0.028	0.002	37.5	10.42	0	0.516	84.07	-0.21	0.00	251.87	0.56
1579.00	105	0.029	0.001	81.5	22.64	-4.9	0.602	85.5	3.06	3.06	25463.90	28.29
1585.00	111	0.031	0.002	39.6	11.00	-0.2	0.669	67.64	-1.94	0.00	-5213.12	-8.69
1591.00	117	0.033	0.002	37.3	10.36	1.5	0.731	61.89	-0.11	0.00	1016.64	1.69
1597.00	123	0.034	0.002	30.4	8.44	-5.1	0.783	51.19	-0.32	0.00	1173.37	1.96
1603.00	129	0.036	0.002	15.2	4.22	-4.5	0.808	25.4	-0.70	0.00	42.33	0.07
1630.00	156	0.043	0.008	12.7	3.53	1.2	0.903	94.84	-0.03	0.00	399.41	3.00
1636.00	162	0.045	0.002	52.7	14.64	-1.5	0.992	89.61	1.85	1.85	9876.57	16.46
1644.00	170	0.047	0.002	34.1	9.47	-3.6	1,059	67.07	-0.65	0.00	8.25	0.02
1649.00	175	0.049	0.001	40.2	11.17	-3.5	1,120	60.82	0.34	0.34	3196.02	4.44
1654.00	180	0.050	0.001	43.5	12.08	-3	1,186	65.82	0.18	0.18	2733.22	3.80
1660.00	186	0.052	0.002	43.1	11.97	-0.6	1,258	71.86	-0.02	0.00	1173.93	1.96
1666.00	192	0.053	0.002	43.8	12.17	0.1	1,331	73	0.03	0.03	1199.90	2.00
1672.00	198	0.055	0.002	36.7	10.19	-0.5	1,391	60.06	-0.33	0.00	43.72	0.07
1678.00	204	0.057	0.002	14.4	4.00	-1.8	1,415	23.56	-1.03	0.00	-649.84	-1.08
1717.00	243	0.068	0.011	3.1	0.86	-1.5	1,448	33.33	-0.08	0.00	93.53	1.01
1726.00	252	0.070	0.003	18.3	5.08	-1.2	1,511	62.99	0.47	0.47	1317.72	3.29
1729.00	255	0.071	0.001	40.2	11.17	0	1,594	82.86	2.03	2.03	7614.44	6.35
1735.00	261	0.073	0.002	46.3	12.86	1	1,668	74.48	0.28	0.28	2544.91	4.24
1741.00	267	0.074	0.002	46	12.78	-1.5	1,747	79.17	-0.01	0.00	1600.69	2.67
1748.00	274	0.076	0.002	46.3	12.86	1.8	1,826	78.9	0.01	0.01	1819.25	3.54

1754.00	280	0.078	0.002	47.3	13.14	-2.1	1,912	85.47	0.05	0.05	2104.29	3.51
1759.00	285	0.079	0.001	58.8	16.33	2.3	2,000	87.93	0.64	0.64	5551.40	7.71
1765.00	291	0.081	0.002	53	14.72	-4	2,087	87.55	-0.27	0.00	1801.19	3.00
1771.00	297	0.083	0.002	46.8	13.00	-2.5	2,164	76.51	-0.29	0.00	960.92	1.60
1777.00	303	0.084	0.002	27.6	7.67	-0.8	2,210	46.4	-0.89	0.00	-1154.38	-1.92
1815.00	341	0.095	0.011	0.7	0.19	-1.9	2,217	6.78	-0.20	0.00	30.24	0.32
1823.00	349	0.097	0.002	6	1.67	1.2	2,231	13.83	0.18	0.18	291.73	0.65
1835.00	361	0.100	0.003	6.9	1.92	1.1	2,253	22.19	0.02	0.02	237.62	0.79
1840.00	366	0.102	0.001	39.8	11.06	1.8	2,314	61.25	1.83	1.83	7473.71	10.38
1846.00	372	0.103	0.002	43.1	11.97	2.7	2,386	71.38	0.15	0.15	2497.75	4.16
1852.00	378	0.105	0.002	39.4	10.94	-2.9	2,453	67.41	-0.17	0.00	1305.80	2.18
1858.00	384	0.107	0.002	3.8	1.06	-12.1	2,459	6.17	-1.65	0.00	-30.80	-0.05
1906.00	432	0.120	0.013	2.1	0.58	-0.6	2,487	27.83	-0.01	0.00	58.74	0.78
1912.00	438	0.122	0.002	40.4	11.22	-6.4	2,554	67.28	1.77	1.77	8891.73	14.82
1918.00	444	0.123	0.002	49.7	13.81	-0.1	2,638	83.41	0.43	0.43	2975.55	4.96
1924.00	450	0.125	0.002	52.1	14.47	0.9	2,726	88.04	0.11	0.11	2094.24	3.49
1930.00	456	0.127	0.002	51.6	14.33	-2	2,811	85.47	-0.02	0.00	1962.45	3.27
1936.00	462	0.128	0.002	44.5	12.36	-2.3	2,885	73.52	-0.33	0.00	691.93	1.15
1942.00	468	0.130	0.002	43	11.94	-1.2	2,957	72.07	-0.07	0.00	1198.75	2.00
1948.00	474	0.132	0.002	54	15.00	1.2	3,045	88.42	0.51	0.51	4054.00	6.76
1954.00	480	0.133	0.002	35.4	9.83	-5.6	3,105	60.02	-0.86	0.00	-49.89	-0.08
1960.00	486	0.135	0.002	35.3	9.81	-2.5	3,164	58.66	0.00	0.00	1536.52	2.56
1966.00	492	0.137	0.002	38.8	10.78	0.3	3,229	65.28	0.16	0.16	1534.93	2.56
1972.00	498	0.138	0.002	36.7	10.19	3.5	3,290	61.18	-0.10	0.00	1613.06	2.69
1978.00	504	0.140	0.002	39.7	11.03	2.9	3,355	65.08	0.14	0.14	2319.04	3.87
1984.00	510	0.142	0.002	14.6	4.06	4.6	3,380	24.37	-1.16	0.00	-485.04	-0.81
1990.00	516	0.143	0.002	14.4	4.00	8	3,404	23.76	-0.01	0.00	1249.96	2.08
1996.00	522	0.145	0.002	42.6	11.83	0.3	3,476	72.59	1.31	1.31	5669.74	9.45
2002.00	528	0.147	0.002	48.2	13.39	-2.3	3,555	79.18	0.26	0.26	3058.18	5.10
2008.00	534	0.148	0.002	48	13.33	-4.8	3,636	81.14	-0.01	0.00	2950.00	4.92
2014.00	540	0.150	0.002	45.8	12.72	-3.3	3,713	76.39	-0.10	0.00	1922.79	3.20
2020.00	546	0.152	0.002	37.3	10.36	1.4	3,774	61.19	-0.39	0.00	115.80	0.19
2026.00	552	0.153	0.002	14	3.89	-0.2	3,798	23.98	-1.08	0.00	-862.23	-1.44
2032.00	558	0.155	0.002	4.2	1.17	-3.7	3,814	15.67	-0.45	0.00	71.15	0.12
2040.00	566	0.157	0.002	20.3	5.64	-3.4	3,855	41.39	0.56	0.56	1966.55	4.37
2046.00	572	0.159	0.002	21.3	5.92	-2.8	3,892	37.25	0.05	0.05	1066.47	1.78
2051.00	577	0.160	0.001	20.9	5.81	-0.4	3,922	29.23	-0.02	0.00	529.58	0.74
2084.00	610	0.169	0.009	2.4	0.67	-0.7	3,944	22.45	-0.16	0.00	47.11	0.43
2089.00	615	0.171	0.001	22.3	6.19	-0.8	3,986	41.85	1.11	1.11	2693.18	3.74
2095.00	621	0.173	0.002	35.8	9.94	-1.3	4,045	59.68	0.63	0.63	3055.83	5.09
2101.00	627	0.174	0.002	35.9	9.97	-3.5	4,105	59.06	0.00	0.00	1875.75	3.13

2108.00	634	0.176	0.002	29.7	8.25	-5.2	4,158	53.85	-0.25	0.00	1347.44	2.62
2113.00	639	0.178	0.001	35.3	9.81	2.9	4,212	53.75	0.31	0.31	2557.83	3.55
2120.00	646	0.179	0.002	21.7	6.03	3.1	4,252	39.94	-0.54	0.00	105.85	0.21
2125.00	651	0.181	0.001	33.5	9.31	1.7	4,302	50.16	0.66	0.66	3049.22	4.24
2131.00	657	0.183	0.002	28	7.78	1.3	4,351	48.33	-0.25	0.00	380.99	0.63
2137.00	663	0.184	0.002	34.8	9.67	-3	4,407	56.05	0.31	0.31	2560.13	4.27
2143.00	669	0.186	0.002	33.4	9.28	-1.6	4,463	56.12	-0.06	0.00	1050.33	1.75
2150.00	676	0.188	0.002	33.9	9.42	1.1	4,526	63.28	0.02	0.02	1164.60	2.26
2155.00	681	0.189	0.001	17.4	4.83	-0.2	4,552	26.29	-0.92	0.00	-849.72	-1.18
2182.00	708	0.197	0.007	3	0.83	-1.1	4,575	22.73	-0.15	0.00	66.03	0.50
2188.00	714	0.198	0.002	13.8	3.83	-1.8	4,598	22.93	0.50	0.50	1093.34	1.82
2194.00	720	0.200	0.002	22	6.11	-1.8	4,635	37.1	0.38	0.38	1524.93	2.54
2200.00	726	0.202	0.002	25.3	7.03	3.1	4,677	41.63	0.15	0.15	1546.92	2.58
2209.00	735	0.204	0.003	8.9	2.47	1.4	4,699	22.19	-0.51	0.00	-49.17	-0.12
2225.00	751	0.209	0.004	2	0.56	0.1	4,707	8.53	-0.12	0.00	30.91	0.14
2227.00	753	0.209	0.001	11.8	3.28	1.6	4,714	7.03	1.36	1.36	1743.93	0.97
2233.00	759	0.211	0.002	11.7	3.25	-3.2	4,734	19.39	0.00	0.00	574.54	0.96
2239.00	765	0.213	0.002	12.1	3.36	-6.6	4,754	20.35	0.02	0.02	943.81	1.57
2252.00	778	0.216	0.004	3.7	1.03	-8.7	4,767	12.98	-0.18	0.00	291.64	1.05
2263.00	789	0.219	0.003	7.9	2.19	-4.8	4,793	25.66	0.11	0.11	560.10	1.71
2269.00	795	0.221	0.002	14.2	3.94	-3.8	4,817	24.03	0.29	0.29	1108.73	1.85
2275.00	801	0.223	0.002	19.3	5.36	1	4,849	31.65	0.24	0.24	988.24	1.65
2281.00	807	0.224	0.002	13.9	3.86	3.1	4,872	23.58	-0.25	0.00	394.16	0.66
2299.00	825	0.229	0.005	3.6	1.00	4.4	4,890	17.88	-0.16	0.00	167.96	0.84
2305.00	831	0.231	0.002	17.9	4.97	5.4	4,920	30	0.66	0.66	2168.48	3.61
2311.00	837	0.233	0.002	19	5.28	0.2	4,952	31.66	0.05	0.05	564.36	0.94
2317.00	843	0.234	0.002	23.1	6.42	-0.9	4,991	39.48	0.19	0.19	1076.96	1.79
2323.00	849	0.236	0.002	26	7.22	0.4	5,033	42.04	0.13	0.13	990.48	1.65
2329.00	855	0.238	0.002	13.1	3.64	2.3	5,055	22.11	-0.60	0.00	-79.98	-0.13
2338.00	864	0.240	0.003	6.4	1.78	2.2	5,071	15.92	-0.21	0.00	158.72	0.40
2344.00	870	0.242	0.002	6.1	1.69	2.4	5,081	9.38	-0.01	0.00	256.05	0.43
2350.00	876	0.243	0.002	6.8	1.89	2.5	5,093	12.14	0.03	0.03	316.52	0.53
2386.00	912	0.253	0.010	2.9	0.81	2.9	5,122	29.2	-0.03	0.00	129.75	1.30
2392.00	918	0.255	0.002	21.6	6.00	3	5,158	36.5	0.87	0.87	2564.92	4.27
2398.00	924	0.257	0.002	15.9	4.42	2	5,185	26.78	-0.26	0.00	293.44	0.49
2404.00	930	0.258	0.002	7.5	2.08	0.5	5,197	12.16	-0.39	0.00	-26.67	-0.04
2410.00	936	0.260	0.002	14.9	4.14	-0.2	5,222	25.07	0.34	0.34	797.73	1.33
2416.00	942	0.262	0.002	21.4	5.94	-1.7	5,258	35.57	0.30	0.30	1328.58	2.21
2422.00	948	0.263	0.002	15.1	4.19	-2.3	5,283	25.24	-0.29	0.00	280.80	0.47
2428.00	954	0.265	0.002	8.5	2.36	-3	5,298	14.3	-0.31	0.00	196.28	0.33
2435.00	961	0.267	0.002	6.8	1.89	-3	5,310	12.01	-0.07	0.00	288.33	0.56

2440.00	966	0.268	0.001	16.6	4.61	-1.6	5,335	25.74	0.54	0.54	1347.95	1.87
2446.00	972	0.270	0.002	18	5.00	0.8	5,365	29.38	0.06	0.06	641.27	1.07
2452.00	978	0.272	0.002	14	3.89	0.8	5,389	24.07	-0.19	0.00	213.86	0.36
2464.00	990	0.275	0.003	6.1	1.69	-0.3	5,409	20.5	-0.18	0.00	71.06	0.24
2470.00	996	0.277	0.002	20.1	5.58	0	5,442	32.7	0.65	0.65	1546.84	2.58
2476.00	1002	0.278	0.002	15.8	4.39	-2.6	5,468	26.22	-0.20	0.00	450.36	0.75
2482.00	1008	0.280	0.002	16.4	4.56	-2.9	5,496	27.7	0.03	0.03	809.45	1.35
2488.00	1014	0.282	0.002	15.7	4.36	-2.8	5,522	26.15	-0.03	0.00	685.40	1.14
2494.00	1020	0.283	0.002	15	4.17	-1.6	5,547	25.35	-0.03	0.00	511.31	0.85
2500.00	1026	0.285	0.002	15.5	4.31	0	5,573	25.63	0.02	0.02	400.55	0.67
2506.00	1032	0.287	0.002	14.3	3.97	0.5	5,596	23.45	-0.06	0.00	334.95	0.56
2512.00	1038	0.288	0.002	8.9	2.47	0.3	5,612	15.12	-0.25	0.00	53.79	0.09
2524.00	1050	0.292	0.003	2.9	0.81	-0.6	5,621	9.45	-0.14	0.00	51.24	0.17
2530.00	1056	0.293	0.002	11.8	3.28	4	5,641	19.71	0.41	0.41	1056.76	1.76
2536.00	1062	0.295	0.002	15	4.17	7.6	5,666	24.8	0.15	0.15	1447.26	2.41
2542.00	1068	0.297	0.002	14.2	3.94	8	5,690	24.11	-0.04	0.00	1200.47	2.00
2548.00	1074	0.298	0.002	10.9	3.03	7.8	5,708	18.04	-0.15	0.00	801.69	1.34
2554.00	1080	0.300	0.002	22.2	6.17	3.7	5,745	37.37	0.52	0.52	2135.70	3.56
2560.00	1086	0.302	0.002	22.2	6.17	0.1	5,781	36.08	0.00	0.00	549.54	0.92
2566.00	1092	0.303	0.002	17.7	4.92	-10	5,811	29.98	-0.21	0.00	1528.20	2.55
2572.00	1098	0.305	0.002	9.8	2.72	-1.1	5,827	16.06	-0.37	0.00	29.99	0.05
2578.00	1104	0.307	0.002	15.4	4.28	-0.7	5,853	25.96	0.26	0.26	780.92	1.30
2585.00	1111	0.309	0.002	42.3	11.75	-1.1	5,929	76.29	1.07	1.07	5078.04	9.87
2590.00	1116	0.310	0.001	44	12.22	-1.3	5,999	69.55	0.09	0.09	1849.33	2.57
2596.00	1122	0.312	0.002	24.7	6.86	5.1	6,037	37.83	-0.89	0.00	-195.52	-0.33
2602.00	1128	0.313	0.002	29	8.06	-4.8	6,085	47.92	0.20	0.20	2274.94	3.79
2608.00	1134	0.315	0.002	20.1	5.58	-6.2	6,118	33.62	-0.41	0.00	800.51	1.33
2614.00	1140	0.317	0.002	16.1	4.47	-6	6,145	26.66	-0.19	0.00	912.35	1.52

A.0.3 HUB motor drawing assembly - Case of Study 1

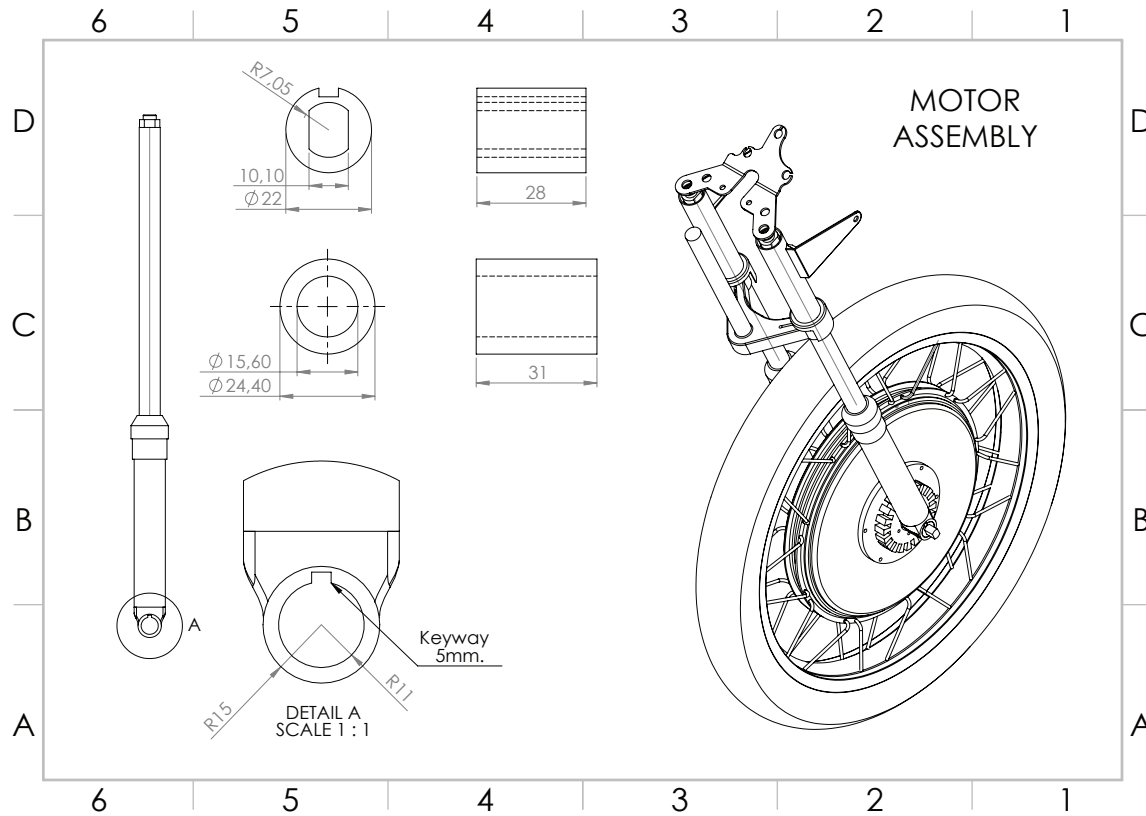


Table A.3: HUB motor drawing assembly - CASE 1

A.0.4 Morphological Chart & Solution Screening - Case of Study 2

Morphological Chart													
Sub-function Solution Concepts													
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13
Row #	Distribute energy	Convert voltage	Protect from overcurrent	Measure break signal	Measure RPM signal	Measure inclination	Measure Torque	Display information	Control the system	Charge battery	Stores energy	Control electric engine	Convert electric energy / mechanical
1	multi socket (1.1)	DC-DC (2.1)	Variable resistor (3.1)	pressure sensor (4.1)	Hall sensor (5.1)	Bosch XDK (6.1)	Torque sensor (7.1)	Speaker (8.1)	micro-controller (9.1)	wind energy (10.1)	Battery (11.1)	PLC (12.1)	electromagnetic generators (13.1)
2	DC-bus (1.2)	linear regulator (2.2)	Fuse (3.2)	Microswitch (4.2)	Infrared sensor (5.2)	Tilt switch (6.2)		Light-emitting diode (8.2)	PLC (9.2)	solar energy (10.2)	pumping water (11.2)	micro-controller (12.2)	
3	cable (1.3)		Disyuntor (3.3)		Inductive sensor (5.3)	Gyroscope sensor (6.3)		Display LCD (8.3)	Analog systems (9.3)	electric energy (10.3)	air compression (14.3)	Analog systems (12.3)	
4			Reed switch (3.4)								flywheel (11.3)		
Solutions screening - Parameter (The kit must be affordable) - 0 = Low, 3 = Medium, 5 = High													
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13
Row #	Distribute energy	Convert voltage	Protect from overcurrent	Measure break signal	Measure RPM signal	Measure inclination	Measure Torque	Display information	Control the system	Charge battery	Stores energy	Control electric engine	Convert electric energy / mechanical
1	3	3	5	3	5	0	3	3	5	0	5	0	5
2	3	5	5	5	3	3		5	0	0	0	5	
3	5		3		3	5		3	0	5	0	0	
4			3								0		
Solutions screening - Parameter (The kit must be minimally invasive) - 0 = Low, 3 = Medium, 5 = High													
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13
Row #	Distribute energy	Convert voltage	Protect from overcurrent	Measure break signal	Measure RPM signal	Measure inclination	Measure Torque	Display information	Control the system	Charge battery	Stores energy	Control electric engine	Convert electric energy / mechanical
1	0	3	5	3	5	0	3	0	5	0	5	0	5
2	3	5	5	5	3	5		5	0	0	0	5	
3	5		3		0	5		3	0	5	0	0	
4			3								0		
Solutions screening - Parameter (The kit must be easy to assembly and disassembly) - 0 = Low, 3 = Medium, 5 = High													
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13
Row #	Distribute energy	Convert voltage	Protect from overcurrent	Measure break signal	Measure RPM signal	Measure inclination	Measure Torque	Display information	Control the system	Charge battery	Stores energy	Control electric engine	Convert electric energy / mechanical
1	0	3	0	0	5	0	3	0	5	0	5	0	5
2	5	5	5	5	3	5	0	5	0	0	0	5	
3	0		0		0	5	0	3	0	5	0	0	
4			0								0		
Subproblem Solutions screening - Parameter (The kit must keep motorcycle driving easy) - 0 = Low, 3 = Medium, 5 = High													
Column #	1	2	3	4	8	9	10	11	13	14	15	17	
Row #	Distribute energy	Convert voltage	Protect from overcurrent	Measure break signal	Measure RPM signal	Measure inclination	Measure Torque	Display information	Control the system	Charge battery	Stores energy	Control electric engine	Convert electric energy / mechanical
1	0	3	0	0	5	0	3	0	5	0	5	0	5
2	5	5	5	5	3	5	0	0	0	0	0	5	
3	0		0		0	5	0	5	0	5	0	0	
4			0								0		

Table A.4: Morphological chart & Solutions screening - Case of Study 2

A.0.5 Electric motor cover drawings - Case of Study 2

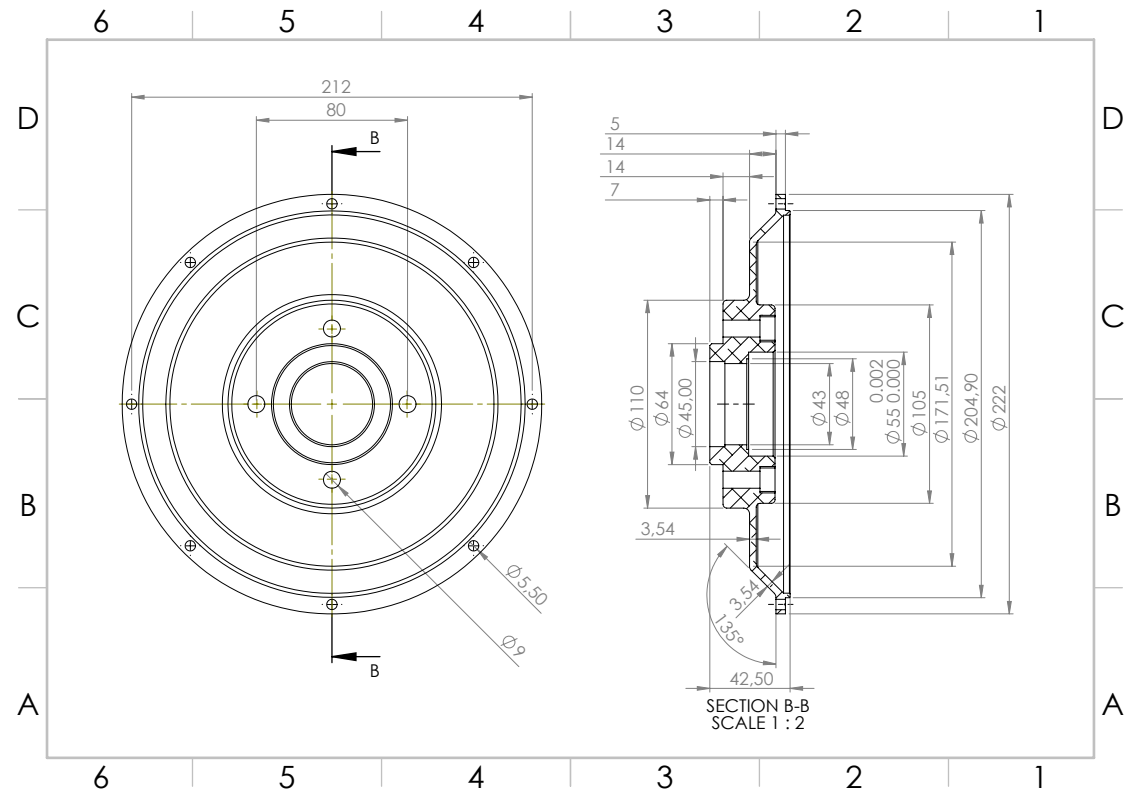


Table A.5: Electric motor case - Case of Study 2

A.0.6 Motorcycle chain adjusters - Case of Study 2

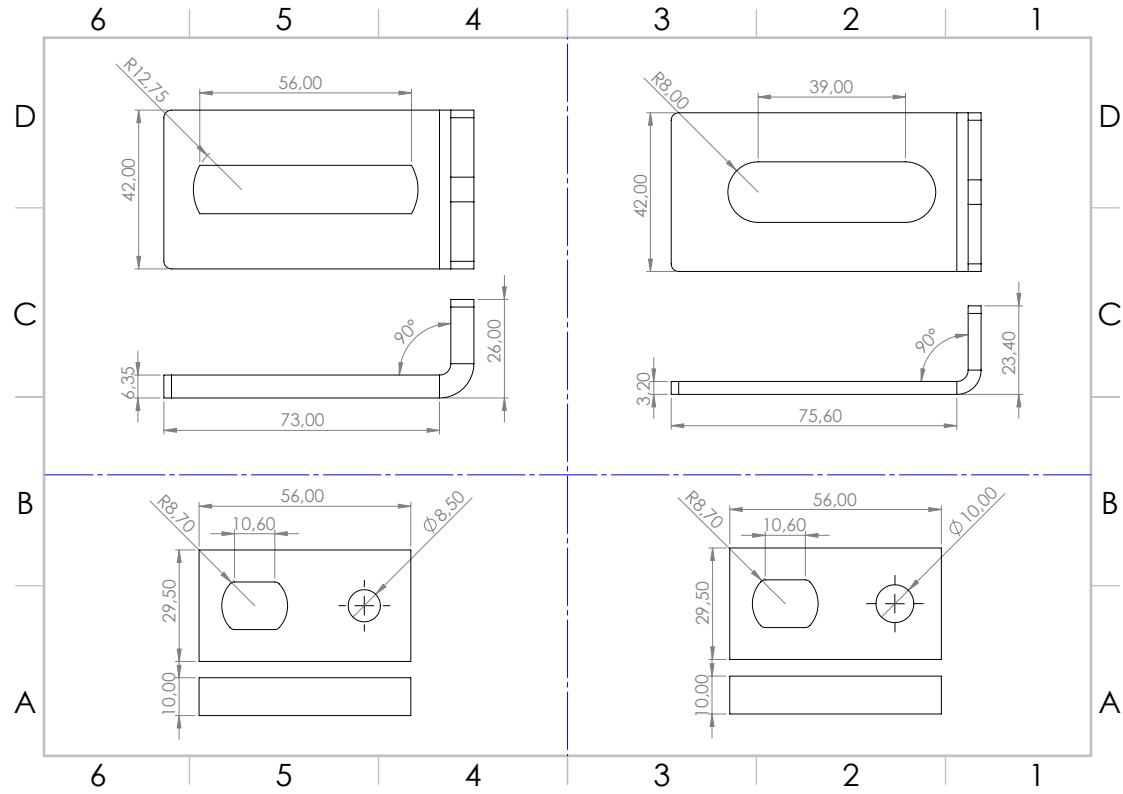


Table A.6: Motorcycle chain adjusters - Case of Study 2

A.0.7 Sabvoton controller wiring diagram - Case of Study 2

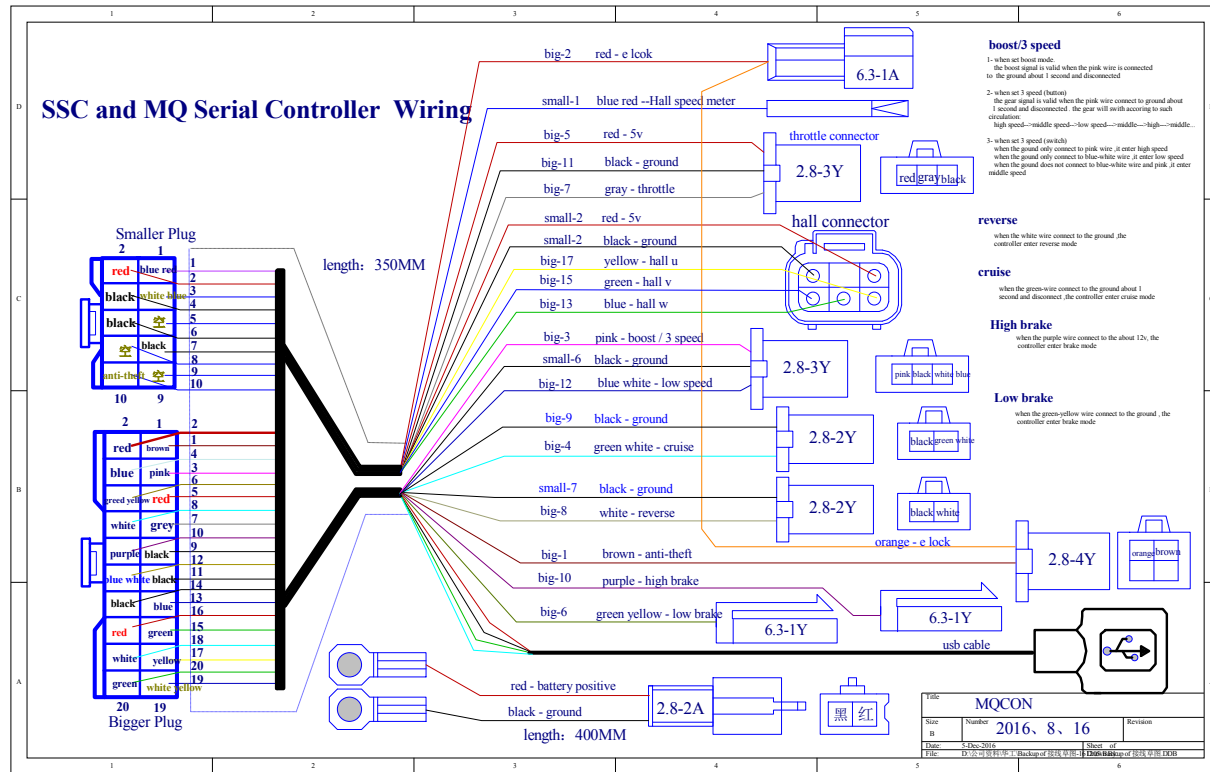


Table A.7: Sabvoton controller wiring diagram - Case of study 2