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Belted Safety Jacket: a new concept in Powered Two-Wheeler passive safety

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Abstract

Powered Two Wheelers (PTWs) offer a viable solution to reduce traffic congestion and promote personal mobility. However, vehicle characteristics and conspicuity issues lead to an overrepresentation of PTWs in accident statistics. This work presents an innovative approach for concept design of new passive safety devices and their development. The landscape of possible design solutions was examined with an in-depth analysis of the state of the art and with the use of conceptual design tools. Candidate solutions underwent a feasibility assessment and they were crossed-checked with the rider needs, identified via a specific on-line survey. The concept of a new passive safety device was born: a Belted Safety Jacket (BSJ). An initial assessment of the device effectiveness for the reduction of riders' injuries was performed by comparison of the main biomechanical indexes (*HIC*, N_{ijmax}, Chest Deflection and Viscous Criterion) in a relevant accident configuration, reproduced in a virtual environment, with and without the device. Later a full factorial Design of Experiment (DOE) was carried out to understand the influence of the device geometrical variables (i.e. possible design parameters) on the biomechanical indexes. The results demonstrated that the integration of BSJ onto the vehicle has the potential to significantly reduce the occurrence of serious injuries during a PTW accident versus a car, since it prevents the contact of the rider with the opponent vehicle. The analysis of the accident kinematic with BSJ suggests that the device will be beneficial also in accidents with other vehicle types.

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1. Introduction

In the last years, in Italy, in Europe and in the rest of the world, the Powered Two-Wheelers (PTWs) circulating park constantly increased. This phenomenon was strictly linked to the user unremitting demand for mobility. Specifically motorcycles, scooters and mopeds play a significant role in cities around the world, where traffic congestion and parking spaces represent a relevant daily problem. As such, PTWs are becoming a more and more important component of the transport system. However, PTWs inherent instability and the absence of passive safety protective devices or structures represent a challenge for road safety. Riders are at far more risk than car drivers per kilometre ridden in terms of fatalities and severe injuries compared with car occupants (Holgate et al. (2015)). Moreover, although the holistic approach to safety includes different factors (e.g. safe road, improved user training, safe vehicle, etc.), protective systems are still a cornerstone to ensure more tolerance in case of riders' or other road users' errors.

This study aims to deepen previous knowledge in Powered Two-Wheeler passive safety with an innovative approach in this field, capable to systematically explore all possible design solutions, in order to find new devices/systems able to increase rider safety. In the first section, the tools and methods employed in the research will be presented. Specifically, the conceptual design tools used to solve the main problem of riders' accident injury mitigation, will be introduced. Initially an in-depth research of the state of the art in passive safety applied to PTWs was carried out. Subsequently, a specific survey, based on the principles of Kano's theory (Kano et al. (1984)), was created to evaluate candidate factors to improve customers' level of satisfaction on passive safety devices: the survey was targeted to understand stakeholders' habits, needs, features to be implemented or not in a new design. Lastly the creation of a network of plausible solutions, named Network of Problem (NoP) (Khomenko et al. 2007), allowed to investigate the landscape of possible conceptual solutions and to find new development paths and solutions. The candidate solutions were assessed with weighted criteria emerged from the survey and from the analysis of the state of the art, in order to choose the potentially best one.

In the second section, the new safety device will be introduced, describing the rationale and the overall working principle as well as each component. The device was tested in a Finite Element (FE) virtual environment against a passenger car for a specific crash configuration. A comparative analysis (i.e. with and without the chosen device fitted on the PTW) was performed to evaluate its protective efficacy. Later a full factorial DOE (Design Of Experiment) was implemented to understand possible correlations of device parameters, and their interactions, with its protective performance. DOE results allowed to identify the best performing design for the device with reference to the specific tested impact configuration. Eventually a more accurate analysis of the loads acting on the dummy allowed to extrapolate useful indications for future device development and improvement.

Nomenclature

CSC	Customer Satisfaction Coefficient
DI	Dissatisfaction Index - Coefficient of Dissatisfaction
DOE	Design Of Experiment
DM	Decision Matrix
FE	Finite Elements
HIC	Head Injury Criterion
HMI	Human-Machine Interface
ISQ	Innovation Situation Questionnaire
MC	Motorcycle
MIPS	Multi-direction Impact Protection System
NoP	Network of Problem
OOP	Out Of Position

OTSM	General Theory of potent cogitate - General Theory of Powerful Thinking
OV	Opposite Vehicle
PHPS	Phillips Head Protection System
PTW	Powered Two-Wheelers
SI	Satisfaction Index - Coefficient of Satisfaction
SO	System Operator
TRIZ	Teoriya Resheniya Izobretatelskikh Zadach - Theory of Inventive Problem Solving
TRL	Transport Research Laboratory
V*C	Viscous Criterion
WSM	Weighted Sum Method

2. Tools and Methods

The backbone of this work is comprised of several activities, which are summarized in the schematic diagram of Figure 1. The objective '*Research and the development of a new passive safety device*' was pursued through three different and simultaneous activities. The analysis of the state of the art was fundamental to understand previous research activities in this sector, what is missing and where research is heading. The second activity aimed to understand the rider needs, to translate them in device features and selection/decision criteria. The last activity was the implementation of a map of possible problem solutions (NoP) using TRIZ and OTSM as tools. Hence, with the information extracted from the other two activities it was possible to select the potential best solution.

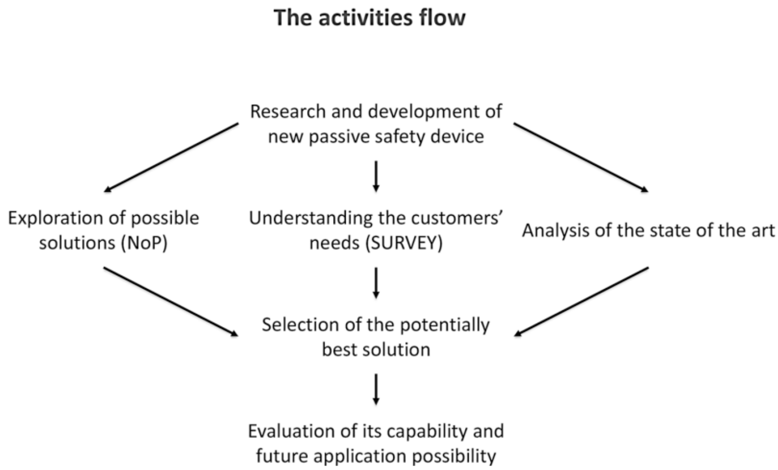

Figure 1. Research flowchart.

2.1. The state of the art

Past research activities on PTW / rider passive safety clearly highlight the difficulty to find safety solutions truly efficient in every accident configuration or at least solutions which are neutral (i.e. not harmful) in off-design scenarios. Over the years, the device development focused on the protection of specific body parts and the solution of specific problems. A rider almost often sustains multiple injuries in an accident (Rogers et al. (1991)) and head injuries are among the leading causes of death in PTW crashes (Ankarath et al. (2002); Piantini et al. (2016)). Despite the efforts made by researchers to improve helmet efficiency and by the governments to legislate their use, head injuries are still often fatal (Aare and Holst (2003)). Helmet is the oldest and the most used PTW passive safety device (the first hard shell of modern PTW helmet dates to the 1930s). Indeed, helmets can reduce fatal injuries by around 44% (Elvik (2009)) and the risk of head injury by 69% (Liu et al. (2008)). Over decades its effectiveness increased due to the improvement in helmet design and materials (Deutermann (2004)). Nowadays, there are four main types of helmets available in the market. From recent studies conducted on this issue (COST327 (2001); Aare (2003)), full face helmets provide better protection than others (modular, open face and half helmet) especially from chin injuries. Indeed, 16% of total helmet damages are located at the chin guard (Richter et al. (2001)). In the last decades, research efforts focused on the implementation of new solutions to enhance the absorption of rotational forces due to oblique impact (Otte et al. (1999)). With reference to this problem, Halldin et al. (2001) presented the Multi-direction Impact Protection System (MIPS), while Phillips (2004) proposed the Phillips Head Protection System (PHPS). Both solutions are based on the friction reduction, introducing an easy-shear layer, outside the helmet shell or between the liner and the shell respectively. More recently, research investigated smart helmets, able to monitor vital signs (von Rosenberg et al. (2015)) or to estimate the amount of impact (Veena et al. (2014)), in order to promptly assess the rider accident injuries and to communicate the emergency through GSM communication.

Rider kinematics after impact depends on several variables (e.g. relative position and speed of the vehicles, if an opposing vehicle is involved) and on the rider actions prior to impact. In the same scenario a loss of control or a controlled fall of the vehicle can drastically change the accident consequences and the reported injuries. Finnis (1990) claims that, in frontal collision, a rider trajectory control and related speed reduction could be a good way to decrease injuries. The airbag represents an effective device to reduce the impact velocity preventing rider injuries. Despite the difficulty of installation on PTWs, the first works carried out by Hirsch and Bothwell (1973) in the 1970s indicated that an airbag could be effective in frontal crashes. This topic was not further developed until 1985 when Chinn published "Motorcycle rider protection in frontal impacts" (Chinn et al. (1985)), and subsequently in the early 1990s, when tests were completed in the UK at the Transport Research Laboratory (TRL). The publications of Finnis (1990) and Happian-Smith with Chinn (1990) described the tests of three different types of PTWs fitted with an airbag. Finnis noted that a conventional airbag design produced a controlled deceleration of the rider and, by increasing the exit height of the rider, it could avoid the impact against the car; in parallel hitting the ground from a greater height could result in more serious injuries. The Happian-Smith's (Happian-Smith and Chinn (1990)) results showed that a full restraint was not possible above a speed of 30 mph, though reducing the speed and controlling the rider's trajectory could still be beneficial. In 2004, Honda developed with TRL the first airbag system for PTW (Chinn et al. (1996)), which was made available since 2006 on the new Gold Wing: a unit in the airbag, positioned to the right of the module, analysed signals from the crash sensors to determine whether or not to inflate the airbag. Four crash sensors, attached on both sides of the front fork, detected changes in acceleration caused by frontal impacts. In 2004 Berg et al. (2004) published the results of tests on an integrated motorcycle airbag. The main purpose was to investigate the effectiveness of airbags for medium-sized motor vehicles. Berg explained that it was not generally possible to apply a car airbag directly to a motor vehicle (although a passenger side airbag had very similar volumes), since it is necessary to take into account the pilot's trajectory, that is not subject to any retention system as it happens in motor vehicles. So, Yamaha carried out a research on the airbag, and in 2007 presented a work by Kanbe et al. (2007) inside the project ASV-3. The authors explained that to reduce the driver damage indexes, in a wide range of collision configurations, it was fundamental to avoid collisions of every part of the body (especially head and chest) against the vehicle, but also to decelerate the rider. To this end, the airbag was made smaller and was placed closer to the pilot than the previous versions. To decelerate the rider, an innovative multi chamber airbag coupled with a back plate was tested. In general, airbags were found to be more effective in 90-degree collisions with a stationary car. Oblique collisions or collisions with a moving car tend to result in a rider sliding around the side of the bag, producing only a little change in rider's velocity. In addition, the cost of fitting an airbag was too expensive in proportion with the PTW cost. In the last decade, the airbag development focused on wearable devices. Although the motorbike airbag jacket was a Hungarian invention (patent registered in 1976 by Tamás Straub), only recently wearable inflatable safety systems for riders caught on. In simpler implementation, these airbags are connected to the PTW by a cable and they are deployed when the cable is detached from its mounting clip. Most recent models are activated by an electronic control unit. Helite, and all major rider garment manufacturers (e.g. Spidi, Brembo, Alpinestars, Dainese) developed airbag jackets for PTW riders. These devices are capable to reduce injuries to important body parts, such as spine, chest, neck and major organs of the upper body, wearable airbags and they are beneficial also to snowmobile riders and horseback riders.

Injuries to the lower extremities are less severe but more frequent, and thus they are relevant for the economic impact. For this reason, several research activities were conducted to protect the lower extremities and some solutions were proposed. A proposed solution incorporated a crash bar into the PTW to prevent the intrusion into the space generally occupied by legs. Craig et al. (1983) observed that this type of protectors was not able to protect the lower extremities. He considered that some forms of shell (e.g. fairing) could help to protect the legs against impacts. Previously also Ouellet obtained similar results (Ouellet (1982)): he investigated 131 crashes involving crash bar equipped motorcycles, and he concluded that the occurrence of leg injuries was not directly related with leg space preservation, because the legs moved out of the initial volume during the accidents. Subsequently, other studies were conducted (Chinn et al. (1985); Chinn and Macaulay (1984); Tadokoro et al. (1985)) to reduce injuries to the lower extremities using protective components installed onto the PTW. These solutions, designed to increase lower limb protection, were often criticized and disputed (Watson (1990)). Ouellet (1990) stated that leg protection structures could worsen overall rider injuries by increasing head and chest impact loads. On the contrary, Nairn (1993) argued that, in accidents with serious leg injuries, their severity could be reduced by approximately 50% if leg protectors were fitted. Subsequent studies showed different possibilities to optimize leg protectors (Otte (1994)), and an overall evaluation of motorcycle leg protectors, based on ISO 13232 (2005), was carried out by Rogers and Zellner (1998). Nonetheless, Hobbs (2001) suggested that further work on these devices was necessary to ensure that leg protectors do not change rider trajectory and result in negative side effects.

The effectiveness of protective clothing to reduce rider injuries was initially stated in 1976 by Feldkamp et al. (1977). They reported results on the reduction of serious injuries in motorcycle crashes thanks to the use of protective clothing. Since then, many studies confirmed the effective of protective clothing in reducing the frequency and severity of some types of injury (Zettas et al. (1979); Aldman et al. (1981); Hurt et al. (1981); Schuller et al. (1982); (1986); Otte and Middelhauve (1987); Hell and Lob (1993)). In the specific, protective clothing are effective to protect soft tissue injuries such as lacerations, contusions and abrasions. In addition, they can prevent or reduce many other injuries including exhaust pipe burns, friction burns, muscle stripping and de-gloving. Another important effect is the reduction of risk infection due to wound contamination and consequent complications in the healing of severe injuries. Schuller et al. (1986) collected crashes and interviews at injured riders to assess the protection provided by these cloths. He concluded that there was a significant injuries reduction, especially for skin and soft tissue. Otte et al. (2001) found that protective clothing can reduce the leg and foot injuries comparing two crashes at the same speed (with and without the device fitted on the rider), and he also reported that riders without protective clothing sustained injuries even in collisions at low speeds. Furthermore, protective clothing can also prevent accidents by maximizing the conspicuity of the rider (Hole et al. (1996)). In Europe, standards were developed for motorcycle protective clothing to promote more abrasion-resistant clothings (gloves (CSN EN 13594 (2015)), jackets, trousers and combi-units (CSN EN 13595 (2002)), shoes (DIN EN 13634 (2016)), limb protectors (DIN EN 1621-1 (2013)), back protectors (CSN EN 1621-2 (2014)) and chest protectors (DIN EN 1621-3 (2015)). Also de Rome et al. (2011) found strong correlation between the use of protective clothing and the mitigation of the injury consequences in terms of post-crash health and well-being.

Over the years, other protective concepts were developed. Neck braces (Geisinger et al. (2007); Leatt et al. (2012)) were developed because conventional clothing (helmets, jackets and back protectors) were not reputed to adequately protect this body region. Despite neck injuries are less frequent than other injury types, they may have serious consequences for the rider. However there is an ongoing debate in the scientific community on neck braces, since it is not clear if their use truly mitigates the risk of neck injuries (Khosroshahi et al. (2016)). On the vehicle side BMW developed the C1 scooter (Kalliske and Albus (1998); Osendorfer and Rauscher (2001)), a PTW with an exceptionally high level of passive safety performance. The vehicle was equipped with an aluminium space frame, safety belts with load limiter and energy absorption elements mounted to the space frame. Thanks to these features, in several countries it was approved for use without a helmet. After selling over 10k units in 2001, BMW only sold 2k units in 2002 and ceased production in October 2002. In general, customers are divvied up between those who love it and those who do not understand its “character”. After C1 concept, other projects were carried out. The first was ZEDIS (Gehre et al. (2001)), a vehicle likewise equipped with safety cell and restraint systems. In the design of this PTW, the lower leg protection section was specially developed by testing plastic foam supports and airbags for the knee area. Another one was the CLEVER project (Hollmotz et al. (2005)). The vehicle, classified as a three-wheeler, was characterized by a technologically advanced tilting system. In crash tests, it received a USNCAP 3 stars safety rating by ensuring a good head and chest protection. Another PTW with above average safety performance is Piaggio Mp3 (Santucci et al. (2009); Di Genova et al. (2007); Sponziello et al. (2008)). It is a tilting three-wheelers scooter with innovative front suspension. The two frontal wheels offer an increased stability and thus an implicit higher safety performance. In conclusion, many studies and ideas on protective safety devices/equipment for PTW and riders were conceived, but rarely they were developed and marketed. Many factors have to be considered for the commercial success of a protective device, apart from the safety performance. If these factors are not taken into account and included into the design process, a bright idea may not be accepted by the market. With this in mind, exploring new opportunities in this sector with an open-minded approach, or importing existing solutions from other matters, may be a good way to find solutions to be implemented.

2.2. The survey

This activity was fundamental to define the evaluation criteria to assess the solutions that will emerge from the NoP. With this objective, customer's needs, extracted from a survey structured on Kano's theory, were considered a good choice. Kano's theory (Kano et al. (1984)) is usually employed to discover customer's needs. It can offer a better understanding of how customers evaluate a product, and it assists companies to focus on the most important attributes to be improved (Gustafsson et al. (1999)). In recent years, Kano's model was widely and successfully applied in strategic thinking, business planning, and product development to provide guidance with respect to innovation, competitiveness, and product compliance (Watson (2003)). Kano's model explains how the relationship between the degree of sufficiency and the customer's satisfaction of a quality attribute can be classified into six categories of perceived quality:

- Attractive (*A*)
- One-dimensional (*O*)
- Must-be (*M*)
- Questionable (*Q*)
- Indifferent (*R*)
- Reverse (*I*)

Where *A* indicates that attribute is an attractive requirement from the customer's point of view and it increase the product success; *O* means that the attribute results in satisfaction when fulfilled and dissatisfaction when not fulfilled; *M* category is for requirements that the customers expect and that are taken for granted; *Q* is for conflicting responses (probably, the interviewed person didn't understand the question or marked out a wrong answer by mistake); *I* means that the customer is indifferent to the attribute and probably he is not willing to pay more for this feature; R indicates that this product feature is not only unwanted by the customer but he even expects the opposite.
Kano's theory was applied in this work to create an on-line survey for powered two-wheeler users. The questionnaire was proposed only in Italian language and it was promoted on the main Italian rider forums. As suggested by Sauerwein et al. (1996), the first step to implement a Kano's questionnaire is the identification of the product requirements. To fulfil this task, over 20 customer's interviews in homogenous segments were carried out, in order to determine approximately 90 - 95% of all possible product requirements (Griffin and Hauser (1993)). These interviews were conducted with 5 main questions to identify customer's problems, as suggested by Shiba et al. (1993):

1. Which associations does the customer make when using the passive safety device/system?
2. Which problems/defects/complaints does the customer associate with the use of the passive safety device/system?
3. Which criteria does the customer take into consideration when buying a passive safety device/system?
4. Which new features or services would better meet the expectations of the customer?
5. What would the customer change in passive safety devices/systems?

Before starting the interview, it was fundamental to understand if the participants were aware of passive safety devices/systems. In case of vague responses, explanations and examples were provided. From these interviews potential problems to solve and some product requirements to be implemented were identified.

The survey was organized in two main parts: the first one focused on the definition of rider's profile, including its mobility habits and its general use of passive safety systems; the second one to collect rider's requirements regarding basic features of new passive safety systems for PTWs. For the second part, a pair of questions were formulated for each product feature: the first question considers the customer's reaction if the product feature was implemented, the second (dysfunctional form of the question) concerns the reaction if the feature was not implemented. By combining the two answers in the evaluation table (Table 1), every product feature could be classified.

Table 1. Kano's evaluation table: A - Attractive; O - One-dimensional; M - Must-be; Q – Questionable; I – Indifferent; R – Reverse.

Customer requirements		Dysfunctional (negative) question				
		Like	Must be	Neutral	Live with	Dislike
Functional (positive) question	Like	Q	A	A	A	O
	Must be	R	I	I	I	M
	Neutral	R	I	I	I	M
	Live with	R	I	I	I	M
	Dislike	R	R	R	R	Q

In the specific, the fourteen pairs of questions focused on the following features of the safety device:

- integration on the PTW;
- obligation to wear it;
- partial limitation of the movements during its use;
- possible re-use after a crash;
- possibility to use/transfer it on other motorcycles;
- functionality dependent on other devices;
- comfort limitation;
- influence on PTW handling;
- influence on the PTW performance;
- modification of the "classic" PTW aesthetic;
- its inexpensiveness (device cost);
- increase of the PTW cost;
- limitation of the visibility;
- integration of multimedia features.

In the second part of the survey, fourteen pairs of questions, formulated according to Kano's method, were included to establish customers' priorities regarding the main features of the passive security systems. To process the results of the survey, Customer Satisfaction Coefficients (CSCs) were used. Each coefficient indicates the strength of a product feature to influence customer satisfaction or, in case of its non-fulfillment, customer dissatisfaction (Berger et al. (1993); Matzler and Hinterhuber (1998); Zhu et al. (2010); Mote et al. (2016)).

To calculate the average impact on satisfaction, it is necessary to add the attractive and one-dimensional answers and divide by the total number of attractive, one-dimensional, must-be and indifferent responses (Eq. (1)). For the calculation of the average impact on dissatisfaction the sum of the must-be and one-dimensional columns has to be divided by the same normalizing factor as shown in Eq. (2). A minus sign in the Dissatisfaction Index (DI) emphasizes its negative influence on customer satisfaction.

$$Customer's\ Satisfaction\ coefficient\ (SI) = \frac{A+O}{A+O+M+I} \tag{1}$$

$$Customer's\ Dissatisfaction\ coefficient\ (DI) = \frac{O+M}{A+O+M+I}(-1) \tag{2}$$

2.3. The Network of Problem (NoP)

Analyses of complex problems, as reduction of rider's injuries, could be a hard challenge. A conceptual map may be useful to tackle the problem and to support a thorough and systematic exploration of the solutions. In the past, several problem-solving methods based on the idea of a map were proposed in engineering systems like loops diagram and KJ diagram (Senge (1990); Andrew (1999)). They were not able to resolve the cognitive gap between the description of the problem and the description of the solution. Theories like TRIZ (Altshuller (1969); (1984); (1986); (1999)) and OTSM (Khomenko (1984); (1987); (1988a); (1988b); (1988c); (1997); (1999); Khomenko et al. (2002); (2006); (2007); Khomenko and Tsourikov (1988); Khomenko and De Guio (2007); Cavallucci et al. (2005)) can help to overcome this problem obtaining an overall picture of the problem to solve, while the Network of Problems (NoP) was selected to represent the problem solutions. The NoP is a semantic map (blocks diagram) of relationships among problems, partial solutions to the problems or a reached objective, each represented by a block, where the focus is to create a network of contradictions, to be cleared in order to solve the problem. The first step in a NoP development is to state, which is the main problem that we want to solve. According to Terninko et al. (1998), in this preliminary stage, the Innovation Situation Questionnaire (ISQ) (Altshuller et al. (1989)) can help to have the right understanding of the problem: it provides the structure for gathering the necessary information to understand in-depth a problem and eventually reformulate and break it down into many smaller problems. When the main problem to solve is clear, a list of the most painful known problems and their potential or partial solutions will be written (Terninko et al. (1998); Khomenko (2014)). Khomenko suggests to present this list as a three column table, as reported in Figure 2. In this case study, the main problem is: "*how is it possible to reduce the rider's injuries during accidents?*". Examples of painful problems may be: "*a rider harmfully hits against the opposite vehicle*" or "*a rider is ejected from the PTW*". About potential/partial solutions, "*personal protective equipment*" is maybe the most obvious. In this first step, problems and potential solutions reported are those emerged from the analysis of the state of the art and the previous knowledge of passive safety devices.

Based on this information, previous solutions to the problem were listed and an overview on potential drawbacks occurred during the use of these devices and systems was generated. In addition, the assessment of all technical solutions found in the state of the art led to the definition of three common macro-functions able to solve the problem. These functions allowed to split the core problem into three main parts. In the specific they are:

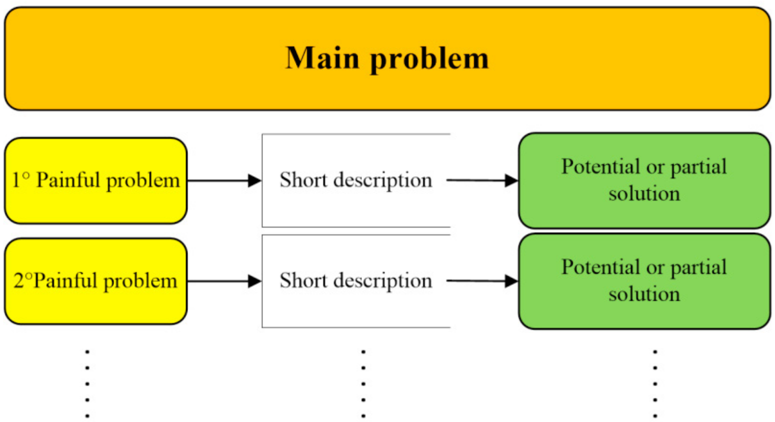

Figure 2. NoP: first development step.

- protect the rider;
- slow-down the rider;
- control of the rider displacement.

Obviously, the division is purely conceptual, since each technical solution could implement more than one function. For each macro-function, a "classical" TRIZ System Operator (SO) was prepared, to find any resources in the various detail levels and in the timeline. In this application, the power of the SO tool was not completely exploited because "passive safety" foresees obligatory the accident event.

Then, all possible solutions, potentially able to avoid the accident, were discarded since they would be in the domain of active safety). For two of the partial solutions identified in the preliminary NoP (air bag and belt), a series of functional models were developed. The functional model allows to identify the possible interactions among the "system" elements and to highlight specific problems of the technical solutions analysed. TRIZ effects database suggested by the Oxford Creativity† was used to find a solution to specific problems. Through this procedure, the network was further extended with other branches. Each contradiction was isolated and analysed with the classical tools like functional model and matrix of solutions, based on the 40 TRIZ principles. This operation allowed to solve, many contradictions, and the NoP was further refined.

At the end of the implementation process, all solutions were going to be assessed on the base of criteria extracted from Kano's survey, and from considerations emerged from the analysis of the state of the art, to determine the potentially best solution.

2.4. Choosing the potentially best solution

The selection of the most promising solution was the last and most crucial phase of the problem-solving process. In this study, the assessment of the potentially better solution was done using the Weighted Sum Method (WSM) (Pohekar and Ramachandran (2004); Borgianni et al. (2015)). This approach is based on the Decision Matrix (DM) and it consists in a set of criteria upon which the potential alternatives can be broken down, scored and summed to obtain a total score used to rank the solutions. The WSM states that, if there are M alternative solutions and N criteria then, the best alternative is the one that satisfies the Eq. (3):

$$A^{*}_{WSM} = Max\sum_{j}^{N} a_{ij} w_{j} \qquad \text{for } i = 1,2,3,\ldots M \tag{3}$$

Where:

A^{*}_{WSM} is the score of the best alternative;
N is the number of decision criteria;
M is the number of alternatives;
a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion;
w_j is the weight of importance of the j^{th} criterion.

The total value of each alternative is equal to the sum of the products. $a_{ij}w_j$ This method presents well known limits related to the weights assignment subjectivity, but it is still the most common approach. The decision criteria were defined according to features identified: 1) from the Kano's survey and the subsequent results analysis; 2) during the development of the NoP; 3) from the state of the art. In case 1) a different weight will be assigned taking into consideration the importance of each category, i.e. for an indifferent category a weight value from one to five will be selected, while for an attractive feature/criterion (more important) the range will be from six to ten. Implementation simplicity of the solution is another important criterion, because it is fundamental to translate the concept solution into a real system. The state of the art contributed to the definition of two decision criteria: the first one based on the effectiveness assessment of each solution (i.e. objective results emerged from previous studies), and the second one on the innovation that each specific solution could lead in the research field. With reference to the latter criterion, the possible device collaboration/integration with other safety devices, was positively rated.

[1] https://www.triz.co.uk/how/triz-effects-database

2.5. Preliminary assessment (first simulation)

Finite Elements Analyses were carried out to assess the effectiveness of the chosen solution, using common biomechanical injury indexes. The virtual environment consisted of five FE models: PTW, dummy, helmet, opposite vehicle and safety device. Both comparative simulations (with and without the safety device) and a variational study to evaluate the response of the design solution to the change of the main geometrical characteristics were run. All simulations were performed using LS-DYNA® software by LSTC (Hallquist et al. (2006); LSTC (2010)).

Belted Safety Jacket (Figure 3) represents the actualization of the best solution emerged from DM. It consists of a sleeveless jacket (vest), to make it lighter and easier to wear. The material used is fabric (polyamide) with mechanical characteristics commonly used for car seat belts. Retractor, pretensioner and slip-ring (0D elements) were constrained to the PTW frame with rigid elements (cyan elements of Figure 3), to simulate mechanical links. Retractor and pretensioner represent the main functional components. They are intended to manage the retentive force exerted by the system. The link between the vest belts was positioned in a central position on the vest back. The slip-ring was positioned just under the seat, while the pretensioner and the retractor were positioned under the seat and near the frame, where a free volume was available.

The PTW model used to conduct the simulations represents a Piaggio Mp3. The virtual model was already validated in previous studies conducted by the Department of Industrial Engineering (DIEF), at the University of Florence (Barbani et al. (2012a); (2012b); (2014a); (2014b)). The Ford Taurus, used as an OV (Opposing Vehicle), was a validated model, distributed free of charge by NCAC (National Crash Analysis Center). The dummy FE model was a numerical reproduction of Hybrid III 50th percentile. The model was developed and distributed by LSTC (Livermore Software Technology Corporation). Its specifications are reported in Guha (2014).

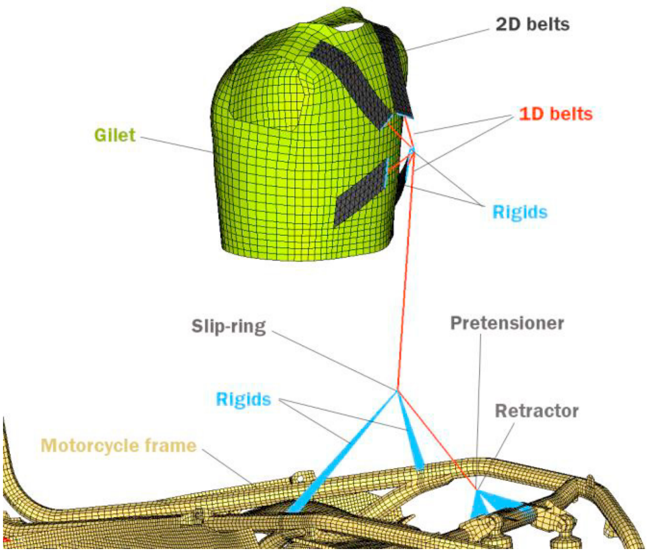

Figure 3. F.E. device model.

The FE helmet model used into the simulations was created by the DIEF. The model reproduces a full-size helmet, and it was validated by reproducing a drop test and a scoring test according to ECE / UN 22 R05 (ECE/ONU 22 (2000); Pratellesi et al. (2011)) regulations: in both cases the results are within the regulatory limits.
For the preliminary efficiency assessment of the safety device, one of the seven basic impact configurations described in the ISO standard 13232 (International Standard of Organization (2005)) was used. Configuration 413 6.7/13.4 was chosen, because it represents one of the most dangerous configuration as highlighted by Barbani et al. (2012a). The protective performance of the device was evaluated comparing the biomechanical injury indexes with and without the device. Four indexes were considered: Head Injury Criterion (*HIC*) (Versace (1971); Hutchinson et al. (1998)), N_{ij} (Biomechanical Neck Injury Predictor) (IIHS (2009)), Chest Deflection (Backaitis and St-Laurent, (1986)) and

Viscous Criterion ($V*C$) (Lau and Viano (1986)).

2.6. Design Of Experiment (DOE)

After an initial assessment, a parametrical study was performed to evaluate the effect of design parameters on the restraint performance of the devices. In literature, it is possible to find many information about the belt anchorage points (three or four) (Rouhana et al. (2003)), about innovative seat belts with independent control of the shoulder and lap portions (López-Valdés and Juste-Lorente (2015); Pipkorn et al. (2016)). These sources highlight the great influence of the geometrical characteristics on the system behavior. Thus, geometrical parameters were included as variable in the study. In addition, since the general objective of the research was to develop a safety device installable on all PTWs, changes in the device layout will be necessary to adapt to the frame of different models. For this reason, the assessment of the device performance with different geometrical parameters is crucial.

A full factorial Design of Experiment (DOE) was chosen since no information about factorial interactions was available. Five factors and two levels were considered. Three out of five factors are linked to geometrical dimensions of the device:

- Longitudinal slip-ring position
- Vertical slip-ring position
- Belts/restraint cable vertical link position

The remaining variables are binary and represent alternative options for system configuration:

- Pretensioner presence
- Vest-belts link position

Although the problem was evidently non-linear, two levels were selected since: 1) the range of the geometrical variables was narrow; 2) the computational time of the finite elements model was high, and a linear approximation was accepted for a preliminary study. The limits of the variability range were determined considering the dimensions of a typical seat. Setting the initial configuration as reference (Figure 4a), the changes for each variable in Table 2 were considered. Their schematic representation can be found in clockwise order in Figure 4, starting from configuration (a).

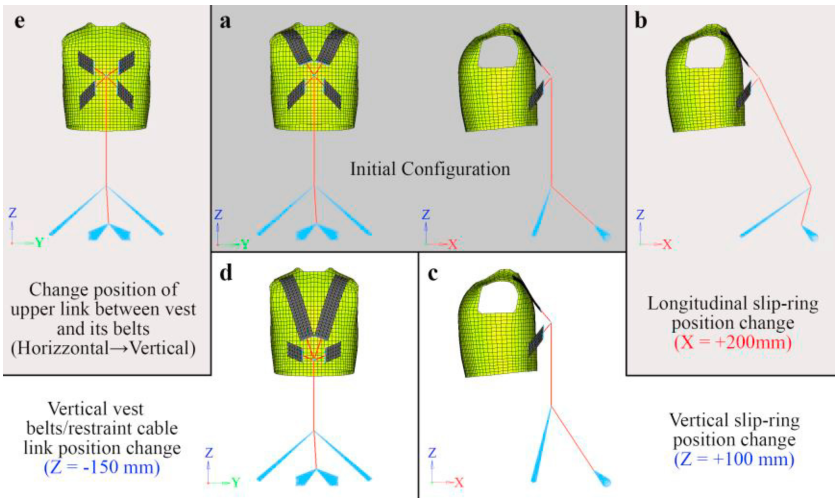

Figure 4. DOE: Representation of geometrical factor changes.

The full factorial design with 5 factors (3 numerical, 2 categorical) with 2 levels consists of 32 experiments (i.e. FE simulations). Replication of the 32 configurations were not considered since the experiment was a finite element calculation and there were no external factors that may be influence the tests. The backward elimination strategy was used to derive an explanatory model of the results: this strategy started with all potential terms in the model and removed the least significant term for each step. The elimination stops when all variables in the model have p-values that are less than or equal to the specified *α to-remove* value. A default *α to-remove* value of 0.10 was considered.

Table 2. DOE: variables/factors considered and their values.

Variable/Factor	Figure 4 reference letter	Factor type	Nomenclature	Min value [mm]	Max value [mm]
Pretensioner presence or absence	Not showed	Text	Pretensioner	No	Yes
Longitudinal slip-ring position	b	Numerical	Slip X	0	200
Vertical slip-ring position	c	Numerical	Slip Z	0	100
Belts/restraint cable vertical link position	d	Numerical	Belts/Cable Z	-150	0
Vest-belts link position	e	Text	Belt/jacket orientation	Horizontal	Vertical

This automatic procedure had two main weak points:

1. If two independent variables were highly correlated, only one of the two could be taken into account within the model, even if both were statistically significant.
2. Special knowledge of the analyst could not be included in automatic procedures. This might result in a model not optimized from a practical point of view.

To solve these two issues, authors reviewed the model at the end of the automatic variable inclusion procedure to be sure that it fit the qualitative requirement previously stated. The acceptability threshold of each model was specified in terms of R^2_{adj} and a minimum value at 0.70 was set. The review procedure included the following steps:

- Automatically fit a hierarchical model with a backward elimination procedure.
- Add a level of interaction until the R^2_{adj} index increases.
- If the highest possible level of interaction was reached and the R^2_{adj} threshold was not reached, increase the *α to-remove* value.

In the presented study, the R^2_{adj} threshold was always reached in the second point, as presented in the results.

3. Results and Discussion

3.1. The survey

Out of 228 answers, only 180 were complete and were considered for the analysis. The first results were on general information about riders: 90% of the participants were men and the remaining 10% women; they were between 19 and 67 years old. Participants were distributed on the Italian territory as follows: 39.8% from the North, 50.6% from the Centre and the remaining 9.6% were from the South. In Figure 5 four pie charts representative of owned PTW type (a), years of riding experience (b), kilometres driven per year (c); estimated use of the PTWs (d) are shown. All results are expressed in percentage of the total amount. In these graphs, it is possible to see a good representation of all PTW styles (Figure 5a), and a uniform distribution of kilometres driven (Figure 5c). Most of the people exceeded 10 years of riding experience (74.44%; Figure 5b). Three use types represented more than 97% of usage: tourism, leisure/hobby/sport, and commuting (i.e. go to work/school/university) (Figure 5d).

Concerning passive safety devices and systems, the results showed that participants know all of them (Figure 6 left side), but their daily use rate was low (Figure 6 right side), especially for those more recently introduced into the market. Lastly the willingness to pay for personal safety equipment was tested. Answers highlighted that over 60% of the participants would be willing to spend between 100€ and 500€ for the new device (30.6% between 100-300€ and 31.7% between 300-500€); the remaining 40% was divided among the other 5 options (5.6% less than 100€, 8.9% between 500-700€, 11.1% between 700-1000€, 9.4% more than 1000€ and 2.7% is not willing to spend for not mandatory safety devices).

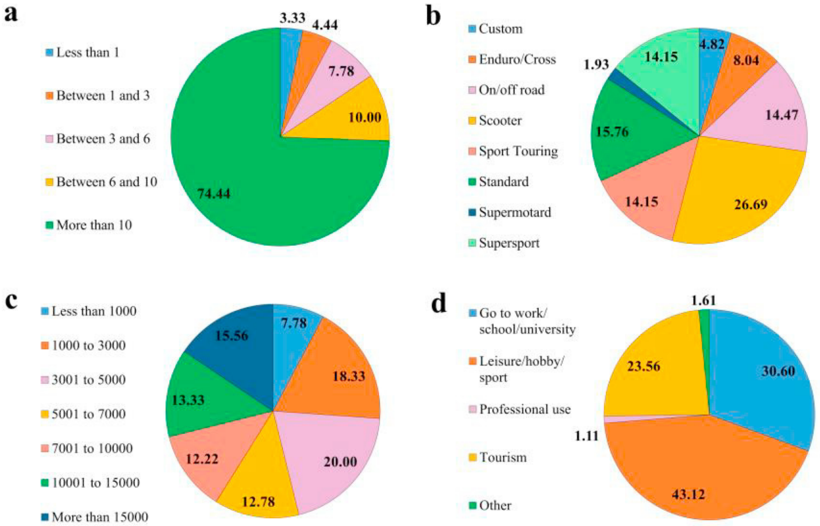

Figure 5. (a) Motorbike types owned (%); (b) Years of riding experience (%); (c) kilometres driven per year (%); (d)PTWs use (%).

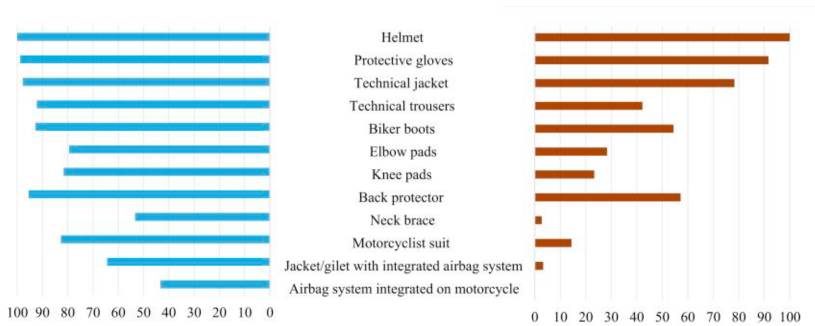

Figure 6. Knowledge of passive safety devices/systems (%) (Left); daily use of passive safety devices/systems (%) (Right).

In Figure 7 are plotted the CSCs obtained from the product quality assessment. The diagram is divided into four quadrants according to the four types of requirements (Attractive, Must-be, Indifferent and One Dimensional). Attractive and Must-be categories are the most relevant as they have the major impact on customers' satisfaction.
In this study, it is possible to see that no One Dimensional or Must-be features were found. Four attractive and four indifferent characteristics were identified. Movement restriction, comfort limitation, influence on performance, vehicle cost increase and influence on aesthetic are totally or almost totally indifferent categories. For this reason, they were not subsequently considered. Visibility limitation category was neglected because its influence is not defined being in the axes origin. Conversely Attractive or One Dimensional categories were used as decision criteria in the solution assessment phase (subsection 3.3).

3.2. The NoP

Figure 8 shows an excerpt of the NoP developed within this study. It was comprised of 116 problems and 154 partial solutions. Thirteen solutions with different degree of development were identified:

- PTW airbag.
- Wearable airbag.

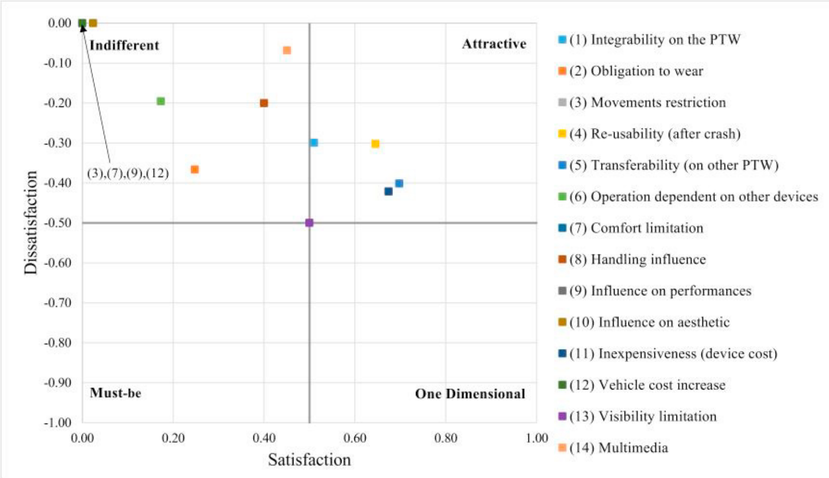

Figure 7: Influence of product features on satisfaction or dissatisfaction.

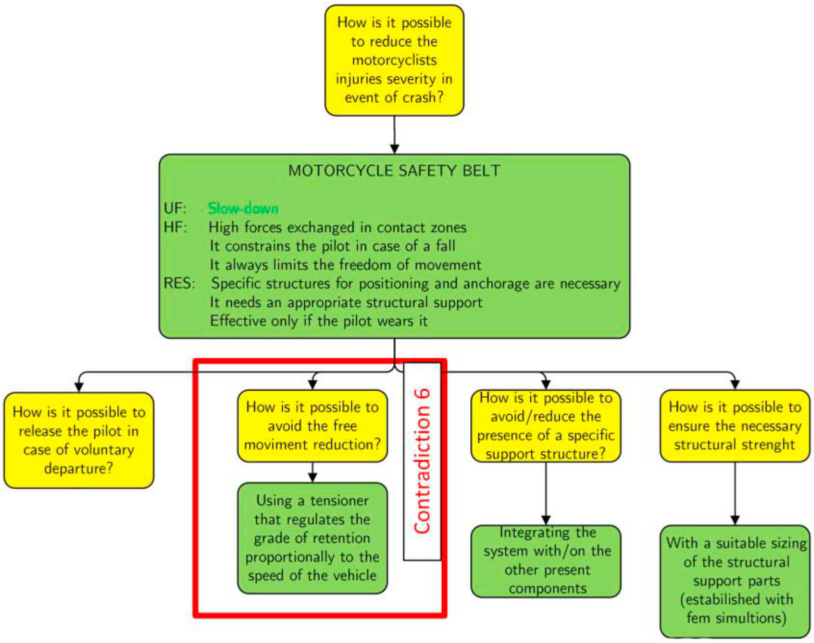

Figure 8: An excerpt of the Network of Problem.

- PTW safety belt/jacket.
- Integrated structural restraint system.
- Increased viscosity of the fluid in the rider's surrounding volume.
- Air overpressure in the rider’s opposite feed direction.
- Electromagnetic attraction / repulsion.
- Integration of safety systems on the O.V..
- Wrap-around protective structure.
- Electroactive polymers to contain rider's movements.
- Rider’s ejection.

- Rider's locking / limiting with vacuum effect.
- Movement seat control with rider fixed on it.

Each of these alternatives were assessed according to the methodology outlined in section 3.3.

3.3. The best solution

In the Decision Matrix eleven decision criteria were considered, as stated in section 2.4, to assess the best solution (

Table 3).

Table 3. Decision Matrix

	Integrability (on the PTW)	Re-usability (after an accident)	Transferability (on other PTW)	Inexpensiveness (device cost)	Multimedia	Obligation to wear	Operation dependent from other devices	Handling influence	Ease of implementation	Effectiveness of the solution	Collaboration/integration with other safety device	A_{wsm} Value
Criteria Weight	7	8	8	7	1	4	3	5	6	10	6	-
Normalized Criteria Weight	0,108	0,123	0,123	0,108	0,015	0,062	0,046	0,077	0,092	0,154	0,092	-
PTW airbag	10	1	1	3	1	10	1	9	6	6	10	5,42
Wearable airbag	3	7	10	8	4	1	6	5	10	7	5	6,52
PTW safety belt/jacket	5	8	7	7	4	3	5	6	9	6	9	6,66
Integrated structural restraint system	10	3	1	5	1	10	1	9	6	5	6	5,35
Increased viscosity of the fluid in the rider's surrounding volume	7	7	2	4	2	5	4	6	1	10	1	5,00
Air overpressure in the rider's opposite feed direction	8	7	2	4	1	5	4	6	3	6	8	5,31
Electromagnetic attraction / repulsion	6	10	3	4	1	4	1	5	1	3	7	4,57
Integration of safety systems on the O.V.	1	1	1	10	1	10	6	10	1	6	9	4,95
Wrap-around protective structure	10	3	1	1	10	10	10	2	5	8	9	5,58
Electroactive polymers to contain rider's movements	10	5	2	2	1	10	1	9	1	7	8	5,43
Rider's ejection	9	2	1	2	3	5	1	7	1	1	4	3,11
Rider's locking / limiting with vacuum effect	6	7	2	3	1	5	4	7	2	3	7	4,42
Movement seat control with rider fixed on it	6	4	2	4	1	5	4	1	6	3	7	4,06

The numbers under each criterion represent their assigned weight (normalized in the third row). Subsequent rows list the proposed solution emerged from the NoP development. In the DM implementation, a range of values from 1 to 10 was chosen to assign both the weight of criteria and to evaluate the performance of each solution with respect to the above metrics. The presented outcomes emerged from a final convergence of opinions among the authors and involved experts in passive safety field. The best solution was the third one. It represents a system based on a safety belt/jacket partly integrated in the PTW (structural and functional components), and partly worn by the rider. Conceptually, it provides a jacket (gilet) realized with strong fabric (but small thickness to limit the weight), very visible (to improve the rider's visibility in the traffic), characterized by belts embeddable into the jacket, and easy to fold and store when it is not used. In fact one of the most important information, collected during the preliminary interviews, was the discomfort associated to all wearable safety devices, being them generally bulky and impossible to store in the PTW when not used. The functional parts of the best solution are represented by typical components of a car seat belt device. To be noticed that the use of standard components will limit the production costs. Specifically, the system is comprised of a retractor and a pretensioner linked to the PTW frame, a slip-ring to constrain the restraint belt in a specific position and a belt/cable to link the restraint active system with the jacket's belts.

3.4. First simulation

In Table 4 the values of the bio-mechanical injury indexes derived from the configuration, defined in subsection 2.5, are listed. *HIC* and N_{ij} percentage reductions are very high while *V*C* reduction is smaller. As easily predictable, Chest Deflection undergoes a moderate increase. In fact, the jacket acts mainly on the dummy thorax. It is important to note that, although increased, the Chest Deflection value is still under the limit (50 mm) defined in the Directive 96/79/EC (1996).
Figure 9 shows a visual comparison of the numerical simulations with and without the device. Since the second frame (50 ms), a restraint effect of the safety jacket is already visible. The remaining frames clearly show that the device is able to avoid the dummy head and shoulder collision against the car. The last frame (200 ms) reports an increase of the motorcycle pitch due to the dummy inertia. Both quantitative (bio-mechanical indexes) and qualitative (video frames) results confirm the effectiveness of the device to reduce rider injuries.

Table 4: Comparison: bio-mechanical injury indexes (W/O and with the device) and relative variation.

Biomechanical Index	W/O	with	Limit	Δ_{value}
HIC	2459	148	1000	-93.96%
N_{ij}	0.68	0.19	1.00	-71.20%
Chest Deflection [mm]	10.20	11.96	50.00	+17.26%
V*C [m/s]	0.13	0.08	1.00	-37.60%

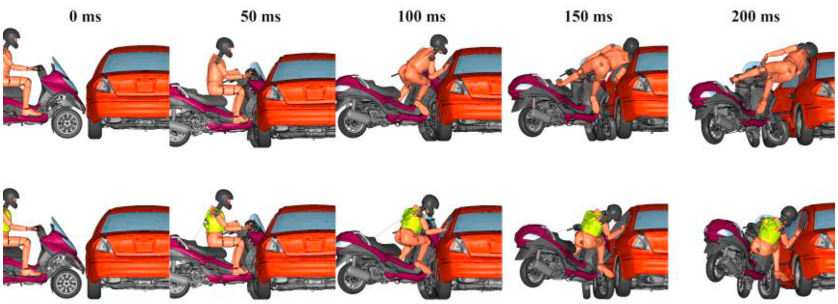

Figure 9. Comparison: video simulation W/O and with device.

3.5. DOE

In Table 5 the input values of the factors and the relative bio-mechanical injury indexes calculated from the FE simulations are reported. Comparing the values relative to *HIC* and N_{ij} indexes, it is possible to see that all the values resulted from the 32 DOE simulations are lower than the simulation without the device fitted (identified as run 0). The results demonstrate that, whatever the device geometrical configuration, the head impact against the car is avoided. In turn, this data suggests that the device may be effective also in other geometric configurations and therefore for other PTW models, although vehicle characteristics will influence the initial rider position and the global inertia, with consequences on the accident dynamics. Results of the chest deflection shows an increase in 71% of the configurations, with reference to the configuration without the device, while for the viscous criterion in only 34% of the cases. Nonetheless the maximum values of both indexes are below the respective acceptability limits. In the R^2_{adj}

value is reported for each of the response variables, together with the model order and the used *α to-remove* value. Table 6 shows that a high interaction level was necessary to explain the variability of the crash event, and that the models are highly representative of the simulations (i.e. high R^2_{adj} values). Implications are twofold: the model well fits reality, which is described partially by the main effect of the independent variables and mostly by their interactions. Thus, model complexity increases and the model could be difficulty used to assess the device behaviour not in correspondence of the variable imposed values. For such a use of the model further simulations or experiments are required.

Table 5. DOE: Input factor values - Output biomechanical injury index values (in grey the initial configuration; run 0 identifies the simulation W/O device).

	INPUT					OUTPUT			
Run order	Pretensioner	Slip X position	Slip Z position	Belts/Cable Z position	Belts/upper link position	*HIC*	N_{ij} *Max*	*Chest deflection [mm]*	*V*C [m/s]*
0	-	-	-	-	-	2459	0.677	10.2	0.125
1	No	0	0	270	Horizontal	117	0.238	14.2	0.186
2	No	200	0	420	Horizontal	140	0.190	18.7	0.141
3	No	0	100	420	Vertical	132	0.209	14.5	0.141
4	No	200	100	270	Horizontal	123	0.154	4.08	0.022
5	No	0	100	270	Horizontal	124	0.182	13.4	0.194
6	No	200	100	270	Vertical	158	0.181	7.62	0.289
7	Yes	200	100	420	Vertical	244	0.246	10.5	0.064
8	Yes	0	100	270	Vertical	288	0.239	13.9	0.112
9	Yes	0	100	270	Horizontal	293	0.240	14.0	0.106
10	Yes	200	0	420	Horizontal	139	0.239	18.2	0.136
11	Yes	0	100	420	Horizontal	399	0.168	12.7	0.084
12	Yes	0	0	420	Horizontal	148	0.190	11.9	0.078
13	Yes	0	0	270	Vertical	182	0.197	19.0	0.164
14	Yes	200	100	270	Vertical	258	0.201	18.2	0.143
15	Yes	0	100	420	Vertical	104	0.157	13.7	0.145
16	No	0	0	420	Vertical	169	0.277	11.2	0.087
17	No	200	100	420	Horizontal	270	0.201	9.49	0.057
18	Yes	0	0	270	Horizontal	173	0.200	17.7	0.122
19	No	0	0	420	Horizontal	113	0.263	16.2	0.152
20	Yes	200	0	420	Vertical	150	0.202	19.3	0.125
21	No	0	0	270	Vertical	147	0.235	12.6	0.113
22	No	0	100	420	Horizontal	160	0.221	13.3	0.080
23	No	200	0	270	Vertical	252	0.157	9.49	0.062
24	Yes	200	0	270	Vertical	260	0.243	8.66	0.052
25	Yes	200	0	270	Horizontal	266	0.253	8.14	0.052
26	Yes	200	100	420	Horizontal	242	0.245	7.81	0.045
27	No	200	100	420	Vertical	160	0.175	11.6	0.077
28	No	0	100	270	Vertical	107	0.184	13.3	0.155
29	No	200	0	270	Horizontal	183	0.133	9.70	0.067
30	Yes	200	100	270	Horizontal	181	0.255	4.52	0.021
31	No	200	0	420	Vertical	165	0.159	12.5	0.100
32	Yes	0	0	420	Vertical	141	0.214	13.0	0.102

4. Conclusion

This research applied a structured design method to develop new solutions for riders' passive safety protection. In this regard, a map (Network of Problem) of possible answers to the problem, based on a problem-solving process, was realized: thirteen possible alternative solutions were identified. To assess all of them and to choose the potentially best solution to be engineered, an online survey constructed on Kano's theory was created. Its results and the information from the state of the art on passive safety devices/systems allowed to extrapolate the product features to be implemented in order to increase the customer level of satisfaction.

Table 6. DOE: R2adj value, factorial terms order and α used for each output variables.

Response variable	R^2_{adj}	Terms order	*α to remove*
Head Injury Criterion	82.6%	4^{th}	0.10
Neck Injury Max	80.9%	4^{th}	0.10
Chest Deflection [mm]	70.3%	4^{th}	0.13
Viscous Criterion [m/s]	89.1%	4^{th}	0.10

By a combination of product features and other assessment criteria, the Weighted Sum Method ranked the candidate solutions and the Belted Safety Jacket was selected. The effectiveness of this solution was evaluated in a virtual environmental. Based on previous studies the 413 6.7/13.4 ISO 13232 configuration was used for the initial assessment of the device. Biomechanical indexes derived from simulation results demonstrated a good protective performance of the device. Specifically, a significant mitigation of the bio-mechanical injury indexes relating to head and neck was reported. Differently, chest is more loaded, although both chest deflection and Viscous Criterion results show that no major trauma is reported by the dummy. As a further step of the device development a full factorial Design Of Experiment was implemented to understand possible correlations among device characteristics and their interactions, and its retentive behaviour.

The results show that main effects of the independent variables on the response is less relevant than the ones of their interactions. Thus, high order terms are necessary to fit reality with a model (high R^2_{adj}), and that the latter cannot be applied outside the variable ranges. In addition, DoE results highlight that the device is able, in any configuration, to avoid the dummy head impact against the car, and thus it reduces the head and neck injury indexes. Increase of the Chest Deflection and Viscous Criterion indexes is possible referred to the configuration without the safety device, but each value is always below the acceptability limits. The device behaviour is robust to changes in the geometrical parameters and thus its portability to other vehicles seems feasible. In conclusion, although the assessment was limited to a single impact configuration, the device significantly reduces the motorcyclist crash injuries. In order to confirm these results, the device has to be tested in other impact configurations and with other vehicles.

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