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## Urban and Extra Urban Vehicles: Re-Thinking the Vehicle Design

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### 1. Introduction

The problems related to transport are reaching unacceptable levels due to congestion, number of accidents with related casualties, pollution, and availability of energy sources. Some small commuter vehicles are already of widespread use, and the steady growth of the number of motorcycles and scooters in the urban areas demonstrates the validity of the lean vehicle approach to solve the problem.

Regardless of their advantages, scooters and motorcycles are affected by several drawbacks, the main disadvantage is related to the safety in dynamic conditions and during crash. Moreover two wheeled vehicles do not have an enclosed cockpit to provide protection from the environment, as cold wind, dust and rain.

For these reasons the demand of personal mobility vehicles must be satisfied by re-thinking the vehicle itself from the beginning, and basing its design on clearly defined basic general needs.

Aim of the present work is to propose a vehicle capable of covering all the different missions typical of a mid size car, including highway and city to city transportation, not confining (limiting) it to the small range usage. The proposed vehicle design starts from the general needs definition.

The mobility in urban environment has to deal mainly with the emissions reduction and the parking problems, the first one can be achieved locally by using a powertrain capable of a zero emission mode, and the second by reducing the vehicle size. Moreover the design of a lightweight vehicle allows the pollution reduction also when using an internal combustion engine. Cities are furthermore characterized by uneven or slippery road and high risk of crashes, therefore the vehicle must provide static and dynamic stability, together with crash protection.

Sub-urban and extra-urban mobility, intended as the working commuting, are characterized by needs that are different from those of the urban environment. Outside the cities the vehicle must be capable of covering a long distance, with reasonable energy consumption, and of travelling at highway speeds, with a high level of active safety, for this purpose an all wheel drive system can increase the levels of safety.

The need of having a closed cockpit to ensure safety and protection, requires a stable position during stops, this leads to the adoption of at least three wheels. To avoid rollover during cornering the vehicle must be able to bank (tilt).

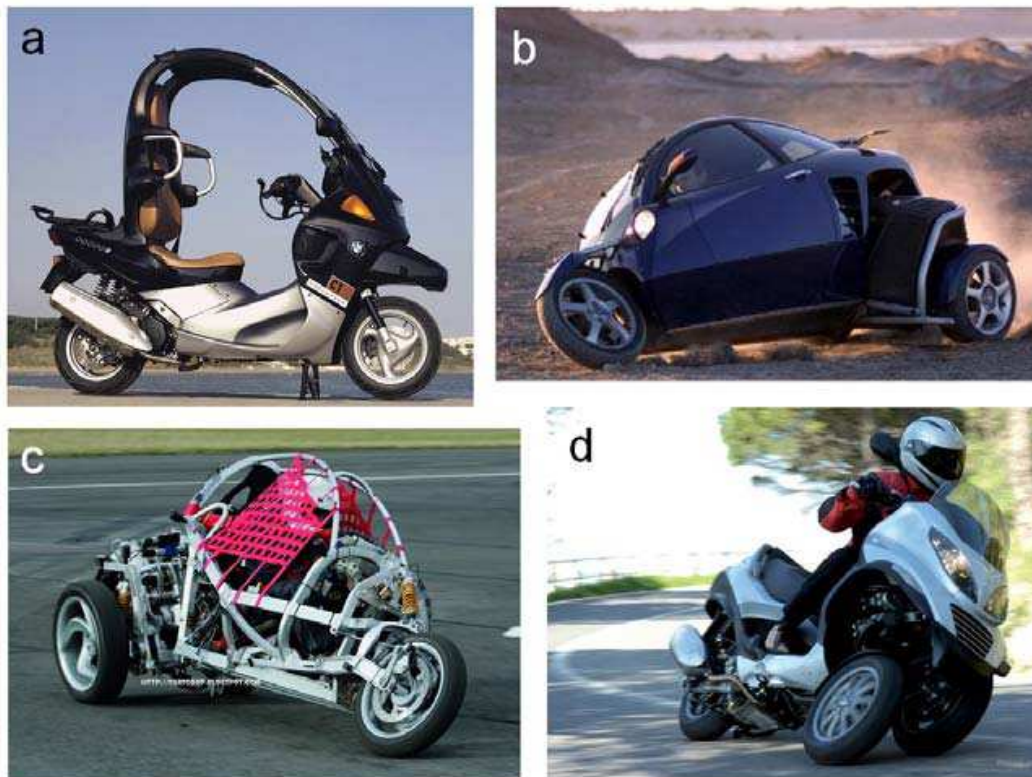


Fig. 1. a) BMW C1, a two wheeled scooter with roll bar, restraint system and front crash box. b) Carver, in production, automatic leaning control. c) Clever, an European project, automatic leaning control. d) Piaggio mp3, actually in production, no roll control.

From the safety point of view the state of the art shows little experience apart from few examples. BMW C1 (Figure 1 a)) is an example of a scooter provided with a closed frame and crash box in order to have structural protection. This kind of solution presents some critical points: vehicle sides are opened, to allow the use of feet during stops, then the height of the mass centre limits the vehicle's agility, and generates some problems in the learning of driving skills.

Since the beginning of the '950 for about twenty years several lean vehicles with more than two wheels were developed (Hibbard and Karnopp, 1996; Riley, 2003). Their failure mainly related to the lack of an available technology.

In last decade, the congestion of urban traffic, the pollution problem, the increment of energy costs and the technology progress motivated a renewed interest in small and narrow vehicles for individual mobility. New concepts were proposed and new configurations were designed (Gohl et al., 2006), a number of solutions have been proposed at prototype or at production level. Most important 1990's prototypes of three wheeled tilting vehicles were the GM Lean machine and the Mercedes F300. In 2002 the Vanderbrink "Carver" was the first tilting narrow vehicle to become a commercial product (Figure 1 b) and the Clever project (Figure 1 c) of University of Bath and BMW applied the same concept to urban mobility. In 2003 the Prodrive concept "Naro" showed the application of tilting to four wheeled vehicles. Since 2006 Piaggio "MP3" is the first three tilting wheels scooter in production (Figure 1 d).

On the powertrain side, electric scooters have been developed to reduce emissions and consumptions. Nevertheless limited autonomy and high cost limit their diffusion. At the

same time the increasing diffusion of alternative fuels, such as ethanol, has demonstrated as a viable way to reduce emissions.

Honda Civic, Insight and CRz, Lexus RX400h, Toyota Prius, are examples of cost-effective solutions with large sales volumes. The application of the full hybrid technology to lean vehicles is promising to further reduce their consumption and emissions.

The design of a hybrid lean vehicle requires the development of a novel design methodology. As a matter of fact this type of vehicle is very different from a car, and even from a motorbike. From this point of view the literature that deals with the design methodology and global optimisation for such kind of vehicle is very rare.

The dynamics of three wheels tilting vehicles can be assimilated to the one of a motorcycle when the wheels camber angle is equal to the vehicle's roll angle. Under this assumption, a reference for the study of narrow commuter vehicles is the literature on motorbike's dynamics. The studies on motorcycle dynamics mainly deals with stability (Cossalter, 1999): in particular weave and wobble oscillations (Sharp, 1992; Sharp & Limebeer, 2004) have been investigated using multi-body models (Sharp & Alstead, 1980; Sharp, 1999; Sharp & Limebeer, 2001; Cossalter et al., 1999; Cossalter & Lot, 2002; Cossalter et al., 2003; Sharp, Evangelou & Limebeer, 2005; Cheli et al., 2006) in order to analyse the motorcycle stability as a function of chassis flexibility (Sharp and Alstead, 1980; Spierings, 1981). On the other hand literature on commuter dynamics is very poor: only analytical first approximation models are available to illustrate specific control issues (Snell, 1998; Karnopp and So, 1997). In particular Karnopp's analysis are devoted to study the DTC (Direct Tilt Control) and STC (Steer Tilt Control) strategies using inverse pendulum models (Karnopp and So, 1997). The most evolved model deals with simplified vehicle's analytical models which neglect relevant effects of the vehicle dynamics (i.e. chassis compliance, dynamic behaviour of the tires, suspension's kinematics) (Gohl et al., 2004).

Objectives of the present work are: 1) define the specifications to be used as reference for designing the vehicle; 2) describe the main design steps and iterations; 3) illustrate the solutions adopted for its main subsystems (frame, suspension system, steering, powertrain, sensors & ECU); 4) validate the design by means of calculations and experiments.

## 2. Functional analysis and target settings

The following section will describe the basic functional needs starting from the previously described mobility environment, trying to obtain some implications which will be then used to define the configuration of each subsystem.

In the urban environment the main request comes from parking problems and traffic, this leads to the need of a small footprint, a dimensions reduction that means the shortening of the vehicle or reducing its width or, possibly, both at the same time.

Reducing the vehicle's width, together with the need of having acceptable cornering performances, suggests to design a vehicle capable of leaning into corners as a motorbike to avoid rollover (Pacejka, 2002; Genta, 2003; Karnopp, 2004). The need of ensuring stability on uneven road and at standstill without the use of a foot on the other hand leads to a vehicle architecture with at least three non aligned wheels. This suspension architecture must comply with the need of banking into corners, and leads to the definition of an important subsystem, the tilting suspension, that, on the vehicle, has to be applied to every axle with more than one wheel.

For the front axle two tilting suspension strategies were considered: passive (free) and active tilting. In the first case, to allow the leaning of the vehicle, a free tilting suspension provides



the roll degree of freedom, as in a two wheels bike. The driver then controls the roll angle by acting on the steering system. In active tilting, the vehicle roll is controlled by connecting an actuator to the suspension. The active control system sets the vehicle roll angle basing its commands on sensors and a suitable control strategy.

Crash and weather protection requirements can only be satisfied by designing a crash proof frame, together with a full fairing enclosed cockpit, the vehicle layout and design of the frame must deal with this specification.

One of the main targets together with traffic and safety is the pollution and fuel consumption reduction. Local emission reduction can be obtained by a hybrid powertrain, for its simplicity and the capability of running at zero emission the most suitable layout seems to be the parallel hybrid, using electric motors and an internal combustion engine. A parallel hybrid electric vehicle may be used as a dual mode commuter. A Zero Emission Vehicle (ZEV) when using only the electric motor (with or without a grid plug in to recharge batteries), or a low pollution vehicle when travelling in Hybrid Electric Vehicle (HEV) mode using both powertrains.

Considering the Extra-Urban environment, some specifications have to be added. To satisfy the need of having a large autonomy together with a maximum speed compatible with extra urban environment and highways the Internal Combustion Engine (ICE) must be sized to reach a high cruise speed without the usage of electric motors, for this reason, together with the higher complexity and costs a series hybrid layout has to be excluded.

An increase of active safety can be obtained by a vehicle dynamics control system, here called Intelligent Vehicle Dynamics (IVD), and an all wheel drive system, together with an active system for the tilt control.

The capability of controlling the current in the electric motors allows to implement independent traction control for the front wheels, avoiding slip during acceleration and cornering. Moreover the parallel hybrid powertrain, when integral traction is active, can work as a set of differentials, providing the correct torque on each wheel, allowing the vehicle to corner properly, and even interact with the vehicle dynamics.

In accordance with the definition of the needs for the vehicle, it is possible to list the main technical characteristics:

- small and lean,
- three wheels,
- active tilting,
- parallel hybrid powertrain capable of behaving as a HEV or a ZEV,
- IVD with anti slip and differentials,
- all wheel drive,
- crash proof structural frame,
- enclosed cockpit.

### 3. Vehicle layout description

The designed prototype vehicle is a compact commuter, weights less than 300 [kg] without the driver, and is able to carry two people. It has three wheels, and all of them are able to tilt together with the frame. The vehicle uses motorcycle tires in order to be able of large roll angles. The chosen layout (Figure 2 and Figure 3) is with two in line seats with the rear passenger's knees surrounding the driver's hips (as in motorbikes), this layout allows to reduce the vehicle cross section ( $S \approx 1 \text{ [m}^2\text{]}$ ) and therefore the aerodynamic resistance if

compared to conventional small urban vehicles. A motorcycle handlebar has been chosen to control the steering, as it allows to control also throttle, brakes, and clutch. According to state of the art studies in vehicle dynamics, due to the acceleration during braking, which is the highest longitudinal vehicle acceleration, a three wheels vehicle should have a single wheel rear axis (Riley, 2003). So the chosen layout is a three wheels vehicle with the front axle having two wheels, this feature requires the design of a front tilting and steering suspension system, but allows the adoption of a motorbike rear end design. This solution helps the design of a lightweight vehicle, and a simple rear transmission layout, avoiding the need of a mechanical differential for the ICE.

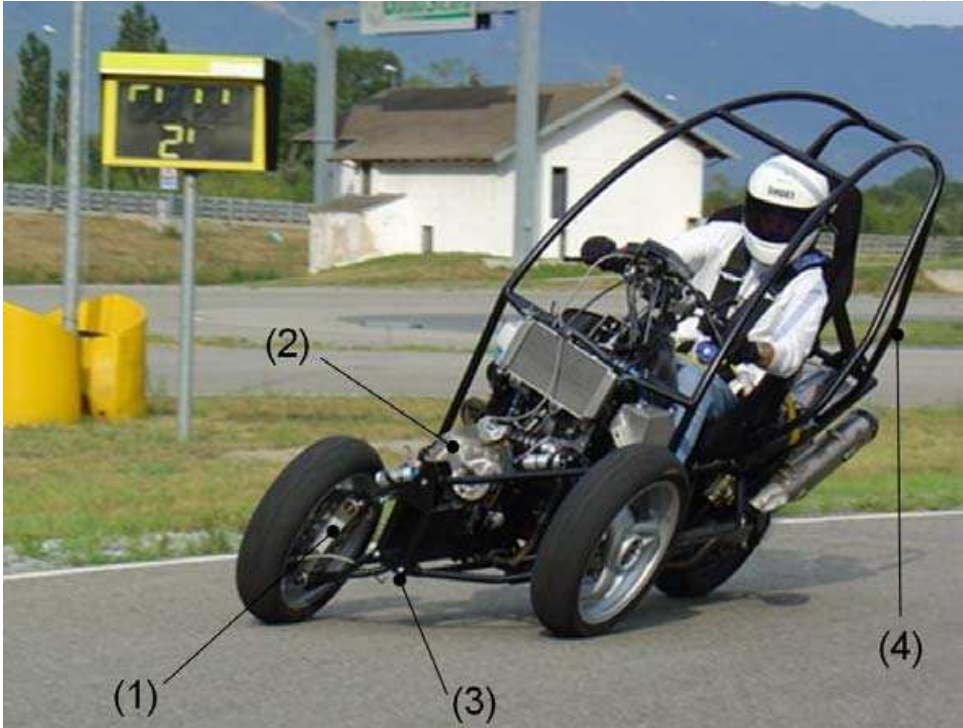


Fig. 2. The vehicle during track tests, front (3) and main (4) frames are visible, the tilt actuator/brake (2) and the hubs (1) are shown.

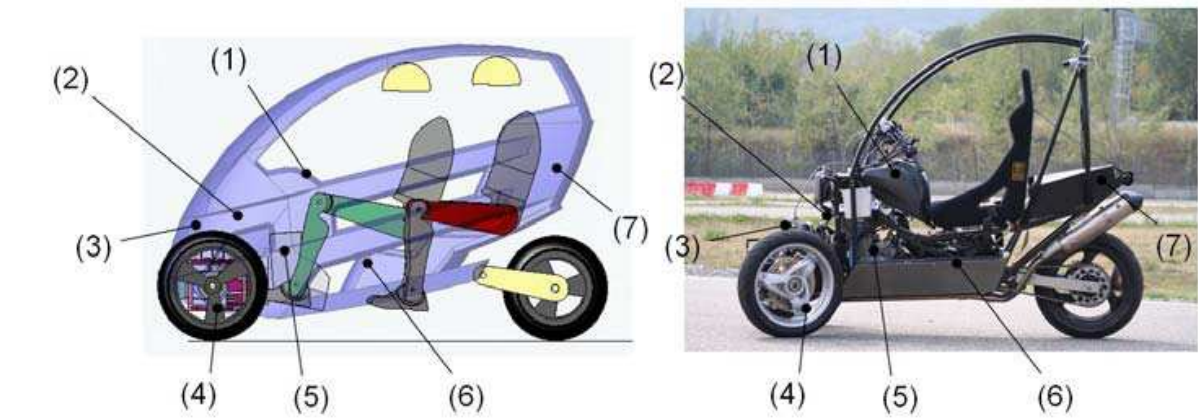


Fig. 3. Vehicle layout showing control handlebars (1), tilt/steer sensors (2), tilt actuator (3), wheels and hubs (4), internal combustion engine (5), room for batteries (6) and passenger/luggage/acquisition system (7).

Vehicle mass	With driver	300	[Kg]
Front track		1.16	[m]
Wheelbase		1.75	[m]
Dimensions	width x length x height	1.2 x 2.35 x 1.6	[m]
Suspensions	Front	Double wishbones	-
	Rear	Swing arm	-
	Max tilt angle vs vertical	45	[°]
Brakes	Front	Double disc 318 mm 2 cylinder floating calipers	-
	Rear	Single disc 245 mm with a single cylinder floating caliper	-
Wheels	Front	Motorcycle 150/60 R17"	-
	Rear	Motorcycle 170/60 R17"	-
ICE	Type	Single cylinder 4 stroke 4 valves water cooled Minarelli Yamaha - Euro2	-
	Displacement	660	[cc]
	Power	35.3 @ 6.000 rpm	[kW]
	Torque	58.4 @ 5.250 rpm	[Nm]
	Transmission	Chain	-
Batteries	Positioned under seat	NiMh	-

Table 1. Prototype characteristics

The design started with the layout described in Figure 3, and has been carried on with the development and integration of a series of subsystems, according to the previously defined technical characteristics, these subsystems can be listed as:

- frame with enclosed cockpit,
- tilting suspension with steering system & tilting actuator,
- powertrain with in wheel motors, internal combustion engine and energy storage unit,
- electronic control units & power electronics.

All the subsystems have been developed starting from a trade off between feasible solutions, then a design and modelling phase together with a test rig validation has defined the final subsystems configurations. A series of track tests has then been performed on the prototype to validate the models and verify its dynamic behaviour. Table 1 shows the overall characteristics of the vehicle.

The subsystem development and prototype configuration is described in the following sections together with a description of the main characteristics.

4. Frame subsystem description

The need of having compact dimensions has led to the adoption of ergonomics similar to the one of a scooter, with the passengers seating one behind the other. To provide passengers support the main vehicle frame structure has been designed basing on a main structural tunnel placed under the seats and supporting the roll bars, the entire prototype frame is a space frame structure based on square and circular section tubes with diameter and side of 30 [mm], and thickness of 1.5mm. The material is 25CrMo4 (25NCd4) TIG welded. Figure 4 shows the frame layout (Renna, 2005).

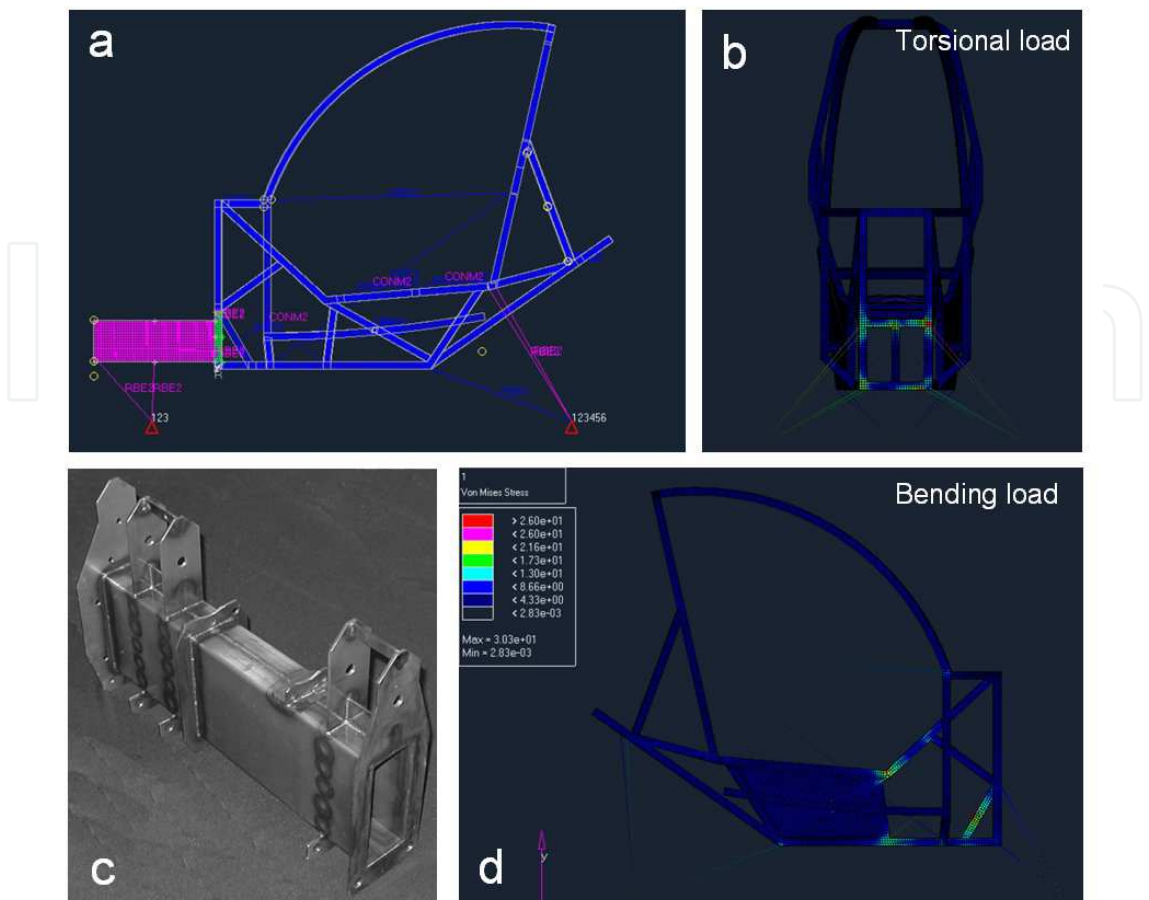


Fig. 4. Prototype enclosed frame a) model side view, b) torsional load FEM front view c) front frame d) bending load FEM side view

The structural support for the front suspension has been realized with a separate front beam carrying also the steering and the tilting mechanism, this structure can be completely disassembled from the main frame to allow the testing of different suspensions configurations. As a three wheels vehicle, the prototype is characterized by stiffness requirements that have been determined by vehicle dynamics issues such as weave and wobble modes. FEM calculations on the frame models have provided a bending stiffness value larger than 500 [kN/m] and a torsional stiffness of 150 [kNm/rad] with an overall frame weight of about 50 [kg]. The stress maximum values have been evaluated too, as it is shown in Figure 4b and Figure 4d.

5. Tilting suspension and actuator description

The capability to lean into corners actively is the main dynamic characteristic of the vehicle, this feature needs the design and implementation of a tilting suspension system, and a tilting actuator together with its control system and power electronics.

The rear suspension is a motorcycle swing arm equipped with a motorcycle mono-shock absorber with a progressive link. The designed suspension is a double wishbone suspension with tuneable castor angle and castor trail, the steering axis has a non null kingpin angle:

- castor trail: 10 to 40 [mm],
- steer ratio: 0.9,
- kingpin: 10°.



The two wheels are connected to two independent motorcycle mono-shock absorbers that are completely tuneable, in springs preload, compression and rebound damping. The designed suspension keeps the wheel mid plane always parallel to the frame, this means that the camber angle of all the three wheels is the same angle of inclination of the vehicle. The vertical ground stiffness is almost constant with suspension travel (Figure 5), the suspension double wishbone architecture shows the typical track variation (Figure 6) and allows the positioning of the maximum track value by means of preload adjustment. With reference to Figure 7, the steering mechanism is based on a lever (1) connected to the steering column (2), the steering rods (3) are linked to this lever and the uprights. To allow the decoupling of the tilting movement from the steering these two joints have been placed one behind the other, aligned with the upper wishbones link to the frame. The steering ratio is almost unity, as in motorbikes. Some Ackermann effect is introduced in the system by the inclination of the lever rotation axis, which gives the inner wheel a "toe out" rotation when steering. Figure 8 shows the obtained behaviour.

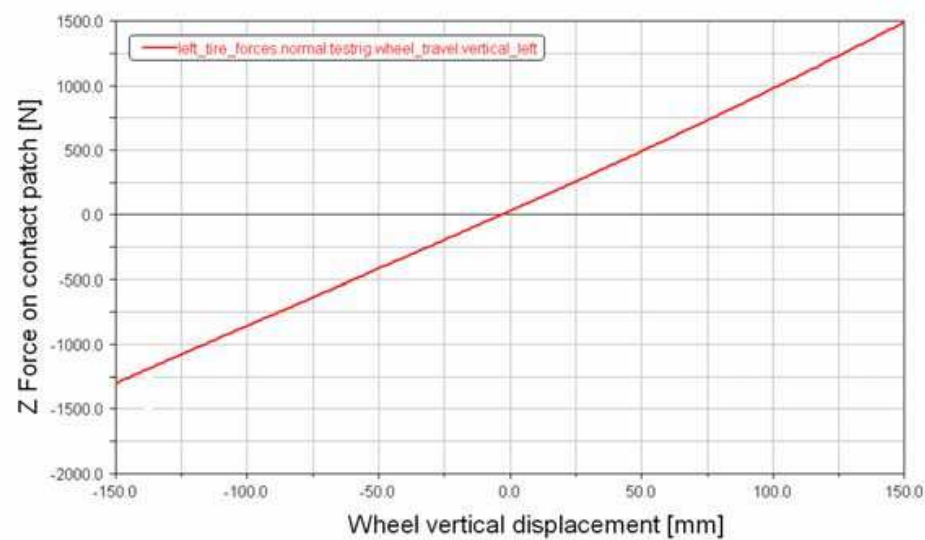


Fig. 5. Front suspension vertical force versus displacement.

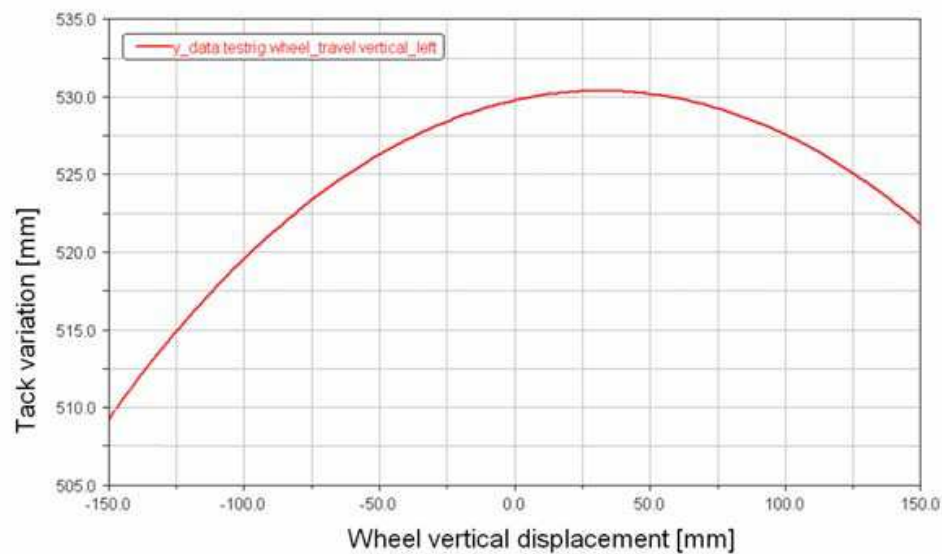


Fig. 6. Track variation versus wheel vertical displacement.

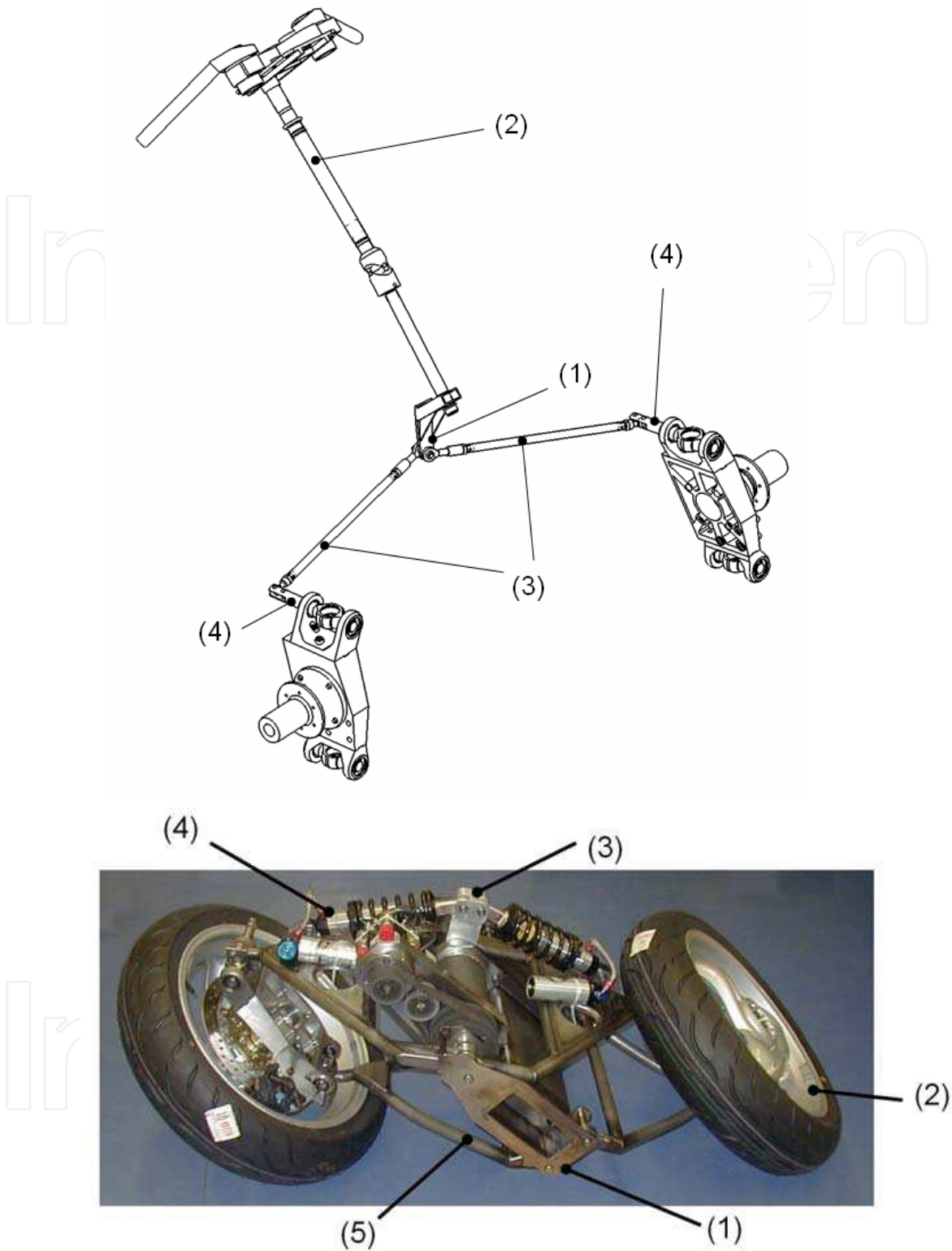


Fig. 7. a) Steering subsystem (1) lever, (2) steering column, (3) steering rods, (4) steering arm. b) Front frame (1) with tilting suspension assembled (2) Front wheels, (3) Tilt crank, (4) Tuneable dampers (5) Wishbones

The steering arm (4) can rotate relative to the upright about a longitudinal axis. This allows large roll angles without influencing the steering mechanism.

A special effort was dedicated during the design of the TTW vehicle to the tilting system design i.e. the device that allows the driver to control the roll angle.

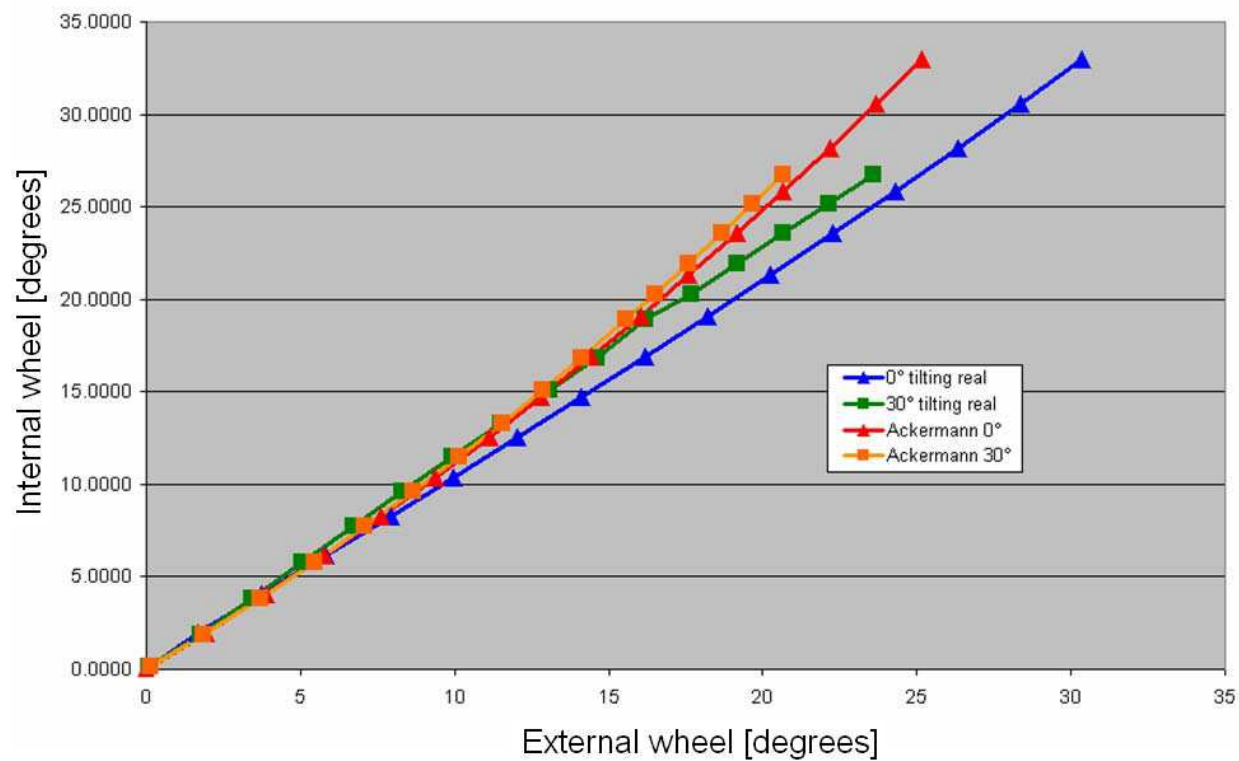


Fig. 8. Steering angle internal wheel versus external wheel at 0° and 30° tilting angles, red and orange reference curves are calculated according to Ackermann’s kinematics.

To control the tilt degree of freedom the shock absorbers are connected to a pivotable support (called tilt crank, as seen in (3) in Figure 7b) whose rotation can be left free or controlled by a tilt actuator. Because the upper wishbones and the tilt crank are rotating about the same axis, there is no coupling between tilting and suspension motion.

Two types of strategies were pursued for tilting: passive and active tilting. In the passive tilting mode no tilting actuator is present. The tilting lever is free to rotate about its hinge axis. The tilting degree of freedom is therefore free. The driver controls the roll angle by acting on the steering system, this is the same as in the case of a motorbike. A mechanical brake allows stable stopping. This configuration has been mainly used for testing and vehicle dynamics model validation.

In the active tilting mode the angle between the tilting crank and the frame is controlled by an electromechanical actuator. In this case the driver acts on the steer as on a car and an active control system imposes the vehicle roll angle during bends.

The tilting actuator design has been based upon the estimation of the two worst working conditions. In the first design load case the tilting actuator must be able to resist the torque corresponding to the maximum centrifugal force without vehicle rollover:

- max lateral acceleration allowed by the three wheels layout: 0.54 [g],
- max lateral force =1600 [N],
- necessary tilt torque = 870 [Nm].

In the second load case the actuator must be able to raise the vehicle from the maximum allowed parking inclination (32°) without rollover:

- necessary tilt torque = 850 [Nm].

The electromechanical tilting actuator has then been prototyped with two brushless motors (for redundancy purpose), connected by means of a belt transmission to a planetary gearbox providing the torque to the tilt crank with an overall ratio of 112/1. The actuator overall mass added to the vehicle is 20 [kg]. The torque required on each motor is then 3.25 [Nm]. Two motors with a maximum continuous torque of 4.76 [Nm] were then chosen. The tilt actuator has been built and tested on a test rig, it is now under track testing.

6. Powertrain description

The powertrain is a parallel hybrid three wheel drive. This hybrid powertrain technology has been chosen to give a further reduction of emissions and consumptions in both urban and extra-urban traffic. The need of a hybrid powertrain together with that of having an all wheel drive vehicle, suggest to adopt two powertrains working in parallel (Figure 10), one with an internal combustion engine and one completely electric, driving different wheels independently. Moreover the elimination of a mechanical power split device helps to reduce the vehicle mechanical complexity and weight.

The solution is based on the development of an in wheel electric motor, here called “power wheel”. The integration inside the front wheels allows reaching of high vehicle roll angles (up to 45°). Different alternatives have been evaluated in terms of type and power, transmission and architecture, the chosen layout is direct drive technology.

The electric motors have been integrated in the wheel hubs to guarantee high tilting angles. The drawback to pay is an increase of the unsprung mass.

The most promising solution in terms of weight and complexity adopts a brushless direct drive motor and a perimeter disc brake in each front wheel.

The power electric wheel based on the use of a direct drive has been completely designed on purpose. Figure 9 shows a 3D view and a section for the right wheel, the space for the electric motor has been obtained by adopting a perimetral brake. In Figure 9b the electric motor is shown together with the bearing, shared with the hub. Table 2 shows the overall direct drive hub characteristics.

Designed brushless electric motor		
Max power	13	[kW]
Max torque at the wheel	130	[Nm]
Unsprung mass	22	[kg]
Added unsprung mass respect idle	3.2	[kg]

Table 2. Direct drive electric motor characteristics.

The parallel hybrid layout requires also the choosing of a suitable internal combustion engine, in terms of type, layout, power and torque, together with its impact on ergonomics and vehicle layout. The internal combustion engine (ICE) together with its own powertrain is here considered as a separate subsystem to be developed and tested. The choice has been



for an off the shelf motorcycle gasoline powered engine, which has been placed immediately behind the front wheels.

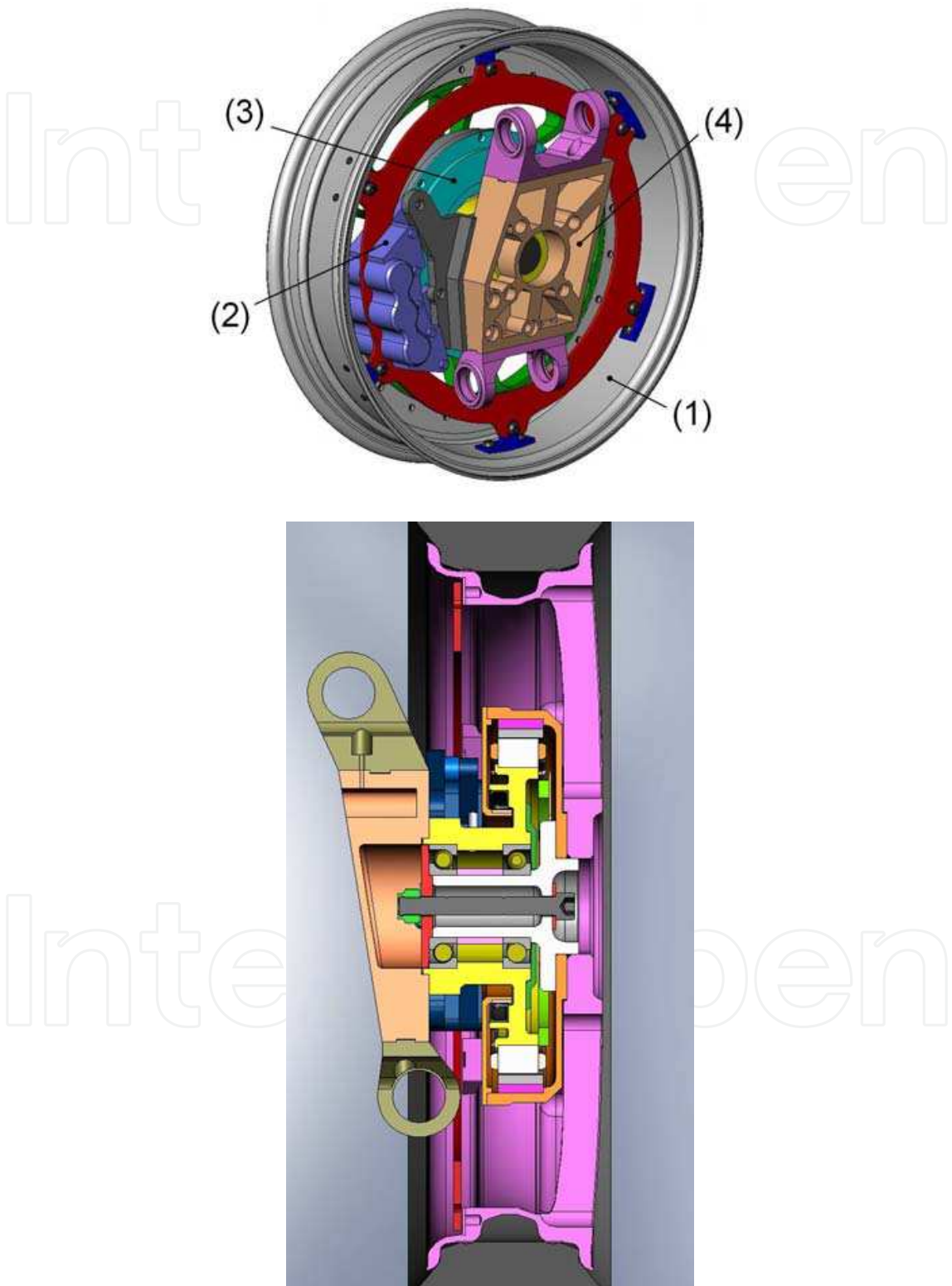


Fig. 9. a) Direct drive power wheel (Right) 1 Rim; 2 Perimeter brake and caliper; 3 direct drive brushless motor; 4 Upright. b) Direct drive power wheel (Right)

Due to its simplicity and weight the adopted solution for the internal combustion engine is a single cylinder, 660 cc gasoline engine, alternative fuels such as ethanol or natural gas are also promising alternatives to be evaluated.

The hybrid powertrain layout is shown in Figure 10, its management is realized by an Electronic Control Unit (ECU). The power source for the ICE is a gasoline tank and an Electronic Storage Unit (ESU) (Figure 11) feeds the electric traction. Two power electronics modules are used for the front electric motors.

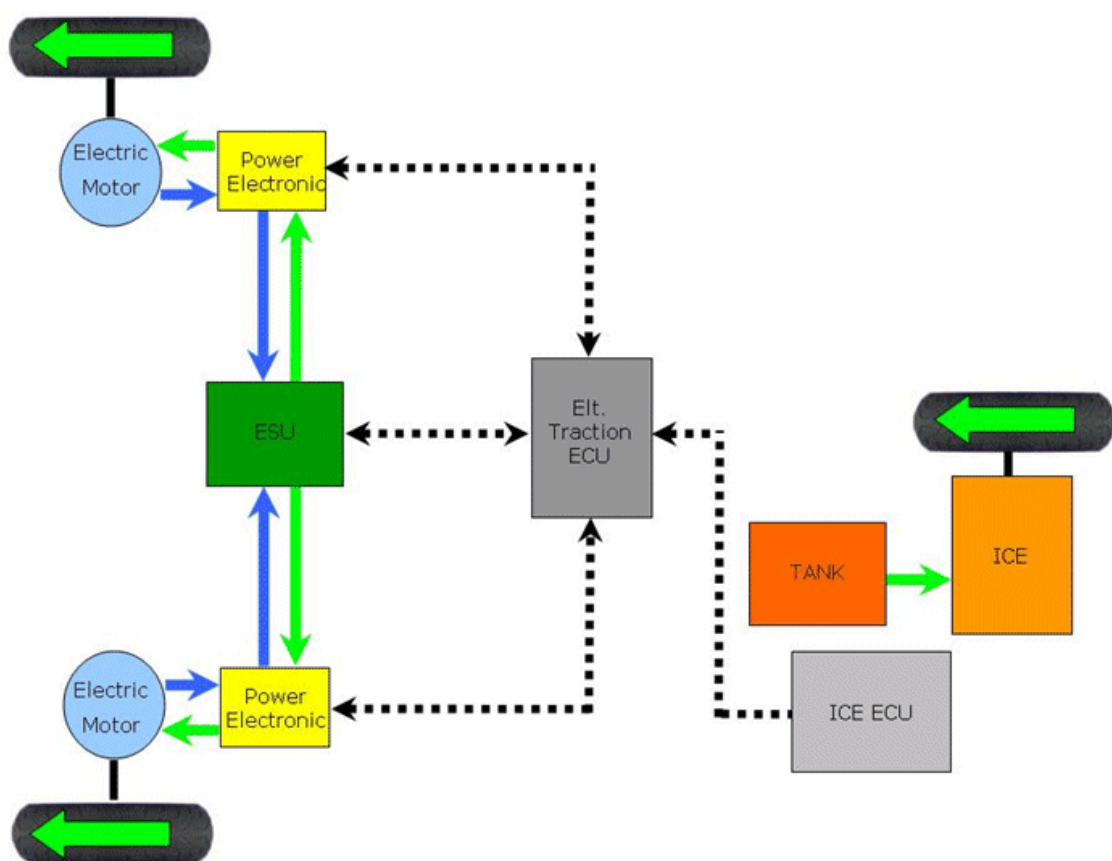


Fig. 10. Hybrid powertrain layout.

To let the driver control both powertrains, electric motors are chosen to behave as “slaves” of the ICE, driver commands and signals from ICE ECU are used to drive electric motors. The driver’s controls (throttle, brake) are used to drive the ICE, and then, to adapt the torque on front wheels to the behaviour of the ICE, the electric traction ECU is able to read the ICE ECU states.

The Electronic Storage Unit (ESU, shown in Figure 11) is necessary for the electric powertrain and can be considered as another subsystem to be developed, the opportunity to use different kinds of batteries, together with super capacitors has been evaluated. The ESU prototype configuration is based on NiMh batteries, the cells are 84 x 1.2 V, with a capacity of 3.2 [Ah]. These batteries have been chosen because of the availability of a high discharge current, important for the electric boost feature implementation. For this prototype the autonomy is limited to 12 km at a constant speed of 50 km/h using only the electric motors (ZEV).

At the moment the hybrid powertrain is performing bench tests for the evaluation of performances, reliability and consumptions, the project is being continued by a small company in Turin in cooperation with the Mechatronics Lab, and has participated to the 2010 Progressive Insurance Automotive X Prize.

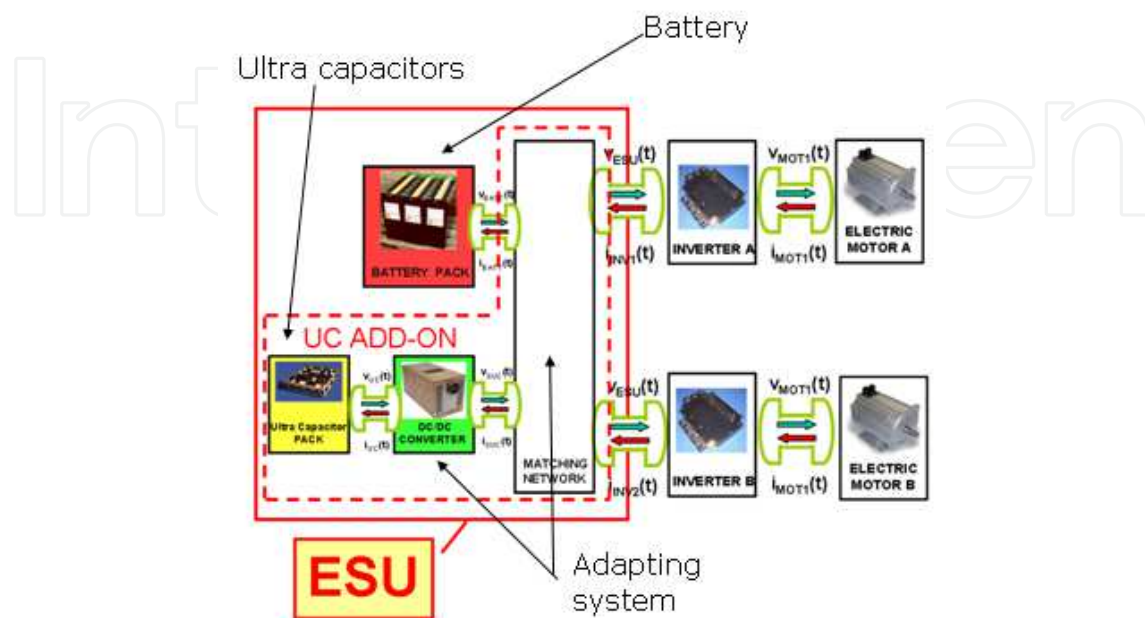


Fig. 11. Electric powertrain layout with Electronic Storage Unit (ESU).

## 7. Conclusions

The present paper describes the main decisions at the base of the design of a hybrid vehicle for urban and extra urban mobility.

The design methodology starts from a functional analysis that sets the main characteristics for the vehicle. The main vehicle subsystems are then described in terms of configuration and design procedure. A series of analytical simulations, FEM analysis, test bench tests and track tests has then been performed to write and validate the models, allowing to verify the static and dynamic subsystems behaviour.

The designed and built vehicle has a mass of 300 [kg] and a trackwidth of 1.16 m, and is capable of transporting two people in a closed cockpit, satisfying the most common car usage with 1/3 of the mass. This means that, from the performance point of view, the power to weight ratio is the same of a 150 kW car. Moreover, if performances are not mandatory, by downsizing the powertrains the mass and consumption can be further reduced, still having higher performance than an usual city car.

Although preliminary the track tests demonstrate that such a vehicle is feasible with available technology and design methodologies.

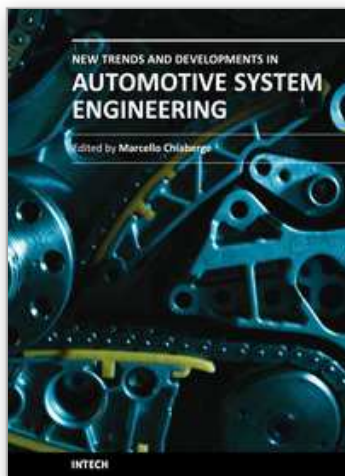
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## **New Trends and Developments in Automotive System Engineering**

Edited by Prof. Marcello Chiaberge

ISBN 978-953-307-517-4

Hard cover, 664 pages

**Publisher** InTech

**Published online** 08, January, 2011

**Published in print edition** January, 2011

In the last few years the automobile design process is required to become more responsible and responsibly related to environmental needs. Basing the automotive design not only on the appearance, the visual appearance of the vehicle needs to be thought together and deeply integrated with the “power” developed by the engine. The purpose of this book is to try to present the new technologies development scenario, and not to give any indication about the direction that should be given to the research in this complex and multi-disciplinary challenging field.

### **How to reference**

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Andrea Festini, Andrea Tonoli and Enrico Zenerino (2011). Urban and Extra Urban Vehicles: Re-Thinking the Vehicle Design, New Trends and Developments in Automotive System Engineering, Prof. Marcello Chiaberge (Ed.), ISBN: 978-953-307-517-4, InTech, Available from: <http://www.intechopen.com/books/new-trends-and-developments-in-automotive-system-engineering/urban-and-extra-urban-vehicles-re-thinking-the-vehicle-design>

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