Purpose Design for Electric Cars

Parameters Defining Exterior Vehicle Proportions

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Abstract—**Vehicle architecture is expected to change in the next years with the introduction of new electric drivetrain systems, but the evolution of car exterior proportions is still uncertain. For this reason, an investigation on purpose design for future electric vehicles is presented. Current trends in automotive design and new challenges in optimized positioning of electric components in car architecture are examined. Using the wheel size as key reference to measure car proportions, traditional and electric vehicles are compared to each other to study the impact of electrification on automotive design. Some relationships between vehicle packaging and exterior design evolution in future alternative cars are identified.**

Keywords—vehicle proportions; alternative vehicles; automotive design

I. Introduction

The powertrain is one of the most influencing systems in car packaging. Hence, the introduction of alternative powertrain technologies will dramatically change the package within a vehicle, previously constrained by conventional combustion engines. In order to forecast the appearance of future alternative cars, it is relevant to understand how electric powertrain concepts will influence the aesthetic proportions of these vehicles and what key functional elements will be the main drivers in the design process. Luccarelli et al. [1] developed a methodology to parameterize traditional car body proportions according to car segmentation. Results showed that conventional vehicles belonging to a given market segment have the same proportions as i) they are inspired by similar reference vehicles and ii) new cars generally agree with certain rules in order to fit the platform they are going to be assembled on. Although the need to cope with efficient propulsion energy usage has pushed for the design of more aerodynamic car silhouettes, most of the alternative vehicles available on the market are still conversion designs of conventional ones. The continuous push for lightweight design [2] and the increasing role of customer oriented design [3] will probably change this trend. Consequently, the aim of this work is to examine the impact of electrification on vehicle exterior proportions of alternative vehicles, identifying some relationships between the placement of new engineering components and the vehicle exterior proportions using the method proposed by Luccarelli et al. [1]. These relationships will be compared with proper conventional vehicles (best selling cars, vehicles of the same market segment, or cars displaying similar features).

This paper is divided into three sections. The first one briefly presents the method proposed by Luccarelli et al. [1] used to analyze car proportions in commercial vehicles. In the second section, alternative vehicle proportions are defined by this method and compared with those of some conventional vehicles used as references. The third part deals with the discussions and conclusions.

II. Methods

When looking at a car the eyes of the viewer operate an aesthetic decomposition, recognizing car body and wheels as main elements in terms of color, trim, and shape. Certainly, the side view of a car gives the largest amount of information in terms of exterior vehicle proportions. Starting from this assumption, Luccarelli et al. [1] developed a methodology to evaluate the vehicle exterior proportion of a conventional vehicle based on simple mathematical relationships. In particular, from the analysis of several car segments, Luccarelli et al. have pointed out that the most important aesthetic features of a vehicle can be parameterized as a function of the wheel size, and peculiar relationships can be defined for each car segment. The aesthetic features included:

- ***A***, the intersection point between the curve *a* (extent of the A-pillar) and the segment OT. O is the center of the front wheel, and T is the point of tangency between the A pillar extent and the front wheel;
- ***b***, the length of the wheelbase;
- ***C***, the vertical projection of the point V on the segment PQ. P is the center of the rear wheel, and Q is the inner point of the rear wheel;
- ***d***, the door height;
- ***g***, the height of the greenhouse;
- ***h***, the overall height;
- ***h1***, the height of the lower door line;
- ***h2***, the height of the lower point of the front lamps;

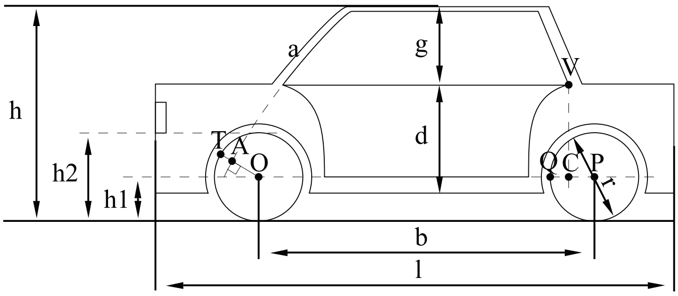

Fig. 1. Key features used for the analysis of exterior vehicle proportions [1].

- ***l***, the overall length of the vehicle;
- ***r***, the wheel size.

Luccarelli et al. also concluded that proper aesthetic design should have a ***g/d*** ratio equal to 1:2, except for the multi-purpose and sport cars where it is 1:1.5 and 1:3, respectively. Moreover, the bottom opening line of the doors ***h1*** should match with the line passing through the centre of the front and rear wheels, except for sport cars where this line is lower. The height position of the front lamps and bumper ***h2*** should be defined by the height of the wheels, except for sport utility and sport cars where it is higher and lower respectively.

Four possible drivetrain layout configurations can be considered to evaluate the exterior proportions of vehicles: *EFF*, front engine and front wheel drive; *EFR*, front engine and rear wheel drive; *EMR*, mid engine and rear wheel drive; *ERR*, rear engine and rear wheel drive. According to the different drivetrain layouts, the extent of the A-pillar (curve *a*) can be tangent to the upper part of the front wheel (*EFF*), it can end near the centre of the front wheel (*EFR*) or in the front part of the front wheel (*EMR*). Considering the C-pillar positioning, the vertical projection of the lower point of the C-pillar (point V) can end near the centre of the rear wheel (*EFR*) or right before the centre of the rear wheel (*EFF*). No results are available for the *ERR* layout, since it is an unusual drivetrain configuration for conventional cars.

III. IMPACT OF E-POWETRAIN ON CAR ARCHITECTURE

Car packaging is an important issue related to exterior design of alternative vehicles; it includes six main systems: powertrain, occupants, wheels and tires, chassis and suspension, body, and interiors and cargo area. Therefore, in this study, several hybrid, battery electric, and fuel cell vehicles have been chosen to stress the impact of these systems on exterior car proportions.

A. Powertrain

The best-selling alternative cars in the automotive market have a hybrid (combustion and electric) powertrain [4]. The architecture of these vehicles is characterized by a limited flexibility in space distribution because a large area is needed to fit the two powertrain systems. The Toyota Prius (1997), considered as the first mass-produced hybrid vehicle, is the most sold hybrid vehicle in the world [5]. It is designed with an aerodynamic silhouette to improve fuel efficiency (cx 0.25). Fig. 2 shows a comparison between this hybrid car and the

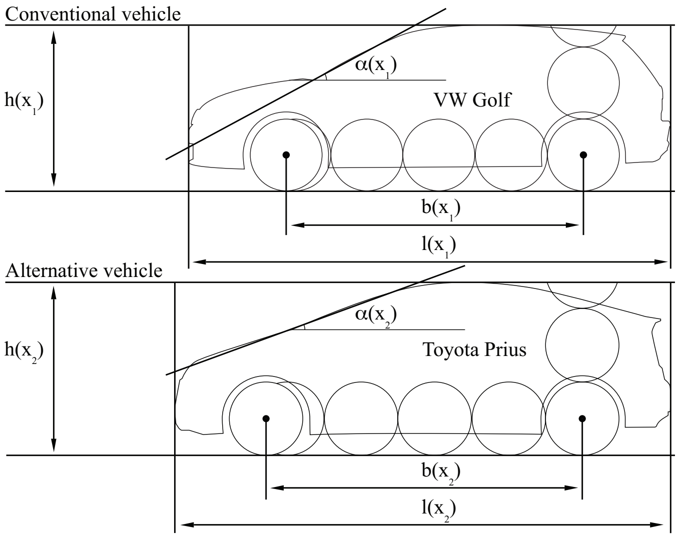

Fig. 2. Comparison between a conventional (x_1) and hybrid (x_2) vehicle.

best-selling conventional vehicle in Europe belonging to the same car segment (VW Golf). According to [1], the following relationships between the aesthetic vehicle parameters and the key reference parameter ***r*** can be defined for the conventional vehicle *(x_1)*:

$$b(r) \approx (4 + 1/4)r \tag{1}$$

$$h(r) \approx (2+1/3)r \tag{2}$$

In the hybrid vehicle *(x_2),* instead, the need to fit the two powertrain systems in the package has increased the overall car dimensions. Thus, the same relationships are

$$b(r) \approx (4 + 1/3)r \tag{3}$$

$$h(r) \approx (2+2/5)r \tag{4}$$

Even if the Prius is higher (***$h(x_1)$***=1452 mm; ***$h(x_2)$***=1490 mm), this vehicle looks much lower than the conventional one. The reasons why the car is perceived as low are the windshield angle ***$\alpha(x_2)$***, the longer car body (***$l(x_1)$***=4255 mm; ***$l(x_2)$***=4480 mm), and the longer wheelbase (***$b(x_1)$***=2637 mm; ***$b(x_2)$***=2700 mm).

B. Occupants

The T shaped lithium-ion battery pack located in the underfloor of the GM Volt (2010) affects interior and exterior design of this vehicle. The car offers only four seats as the battery runs down the center of the vehicle, thus avoiding a conventional rear bench. Moreover, the car body is higher than a conventional one to fit the battery. The greenhouse is kept lower to reach a good drag coefficient (cx 0.28). The higher line, which divides the car body from the greenhouse, usually makes the car look more powerful. The occupants also perceive the car as safer, as this line is usually higher than their shoulders in accordance with R- and H-point of the driver. These are important seating references that influence comfort and visibility from the vehicle into the traffic [6]. With this change, however, the proportion between the height of the greenhouse (***g***) and the door height (***d***) looks uncommon, and hence not proportioned. Indeed, it is not 1:2 as usual [1], but

$$g/d \approx 1/3 \tag{5}$$

As a piece of plexiglass is integrated in the upper car body, the viewer has the impression that the greenhouse is bigger and the 1:2 proportions appear to be satisfied, Fig. 3.

The Renault Twizy Z.E. (2011) is not a proper car; legally it is classified as heavy quadricycle (L7e homologation). However, it is presented in this work since it was the top selling battery electric vehicle in Europe in 2012 [7], and counts as one of the latest attempts to design new compact solutions to accommodate social and environmental changes (such as the ageing population and regional locations). This ultra-compact battery electric car has a rear wheel drive and a mid-engine, while the two occupants are arranged in tandem, Fig. 4. Its frame and body offer occupants extra protection with a deformable structure but, due to the big removable side windows needed to facilitate the access of the two passengers, the perceived relationship between ***g*** and ***d*** is

$$g/d \approx 6 \tag{6}$$

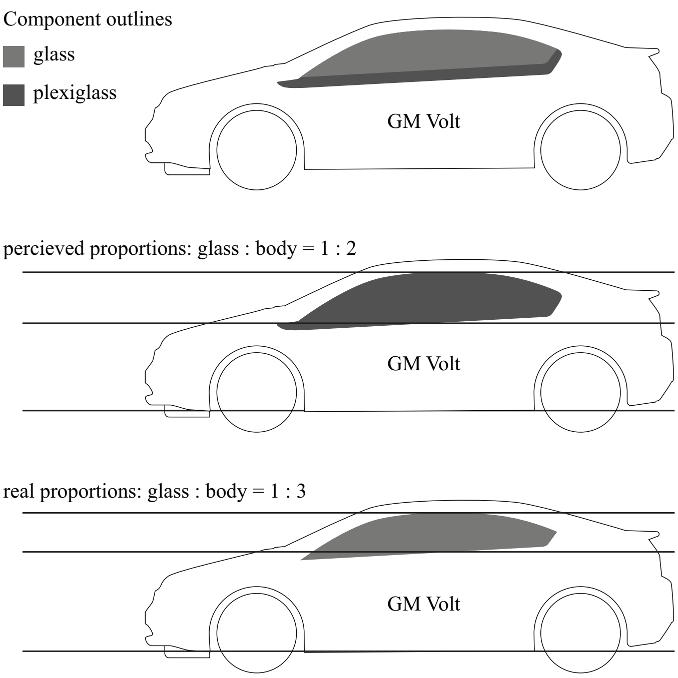

Fig. 3. Real and perceived proportions between ***g*** and ***d*** parameters in the GM Volt.

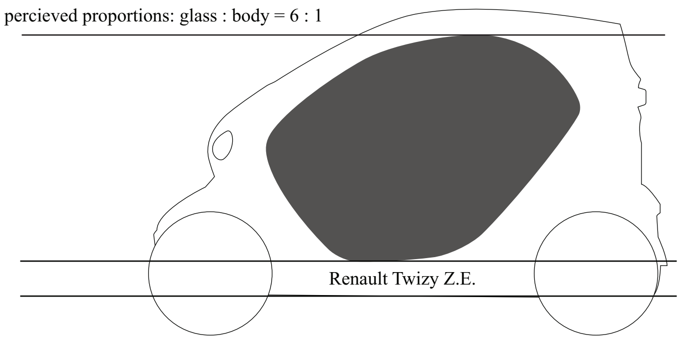

Fig. 4. Exterior proportion analysis of the Renault Twizy Z.E.

C. Wheels and tires

Although battery electric and fuel cell vehicles could allow to gain a high level of flexibility in interior space distribution through high-end drive-by-wire systems [8], their architecture is strictly related to the evolution of energy storage technologies. The battery is still the main technical bottleneck in the usage of an alternative drivetrain. It can dramatically change the overall car proportions, as it is in the case of the full electric BMW i3. According to its size, this vehicle can be compared to the VW Golf (C market segment), Fig. 5. The electric vehicle is very tall compared to the conventional one ($\boldsymbol{h(x_1)}$=1452 mm; $\boldsymbol{h(x_3)}$=1578 mm), due to the space needed in the chassis for placing the battery underneath the floor. The big wheel size of the i3 ($\boldsymbol{r(x_1)}$= 631.9 mm; $\boldsymbol{r(x_3)}$== 699,6 mm)[1] makes the proportions between overall height and wheel size similar in both cars:

$$h(x_1) : r(x_1) \approx h(x_3) : r(x_3) \tag{7}$$

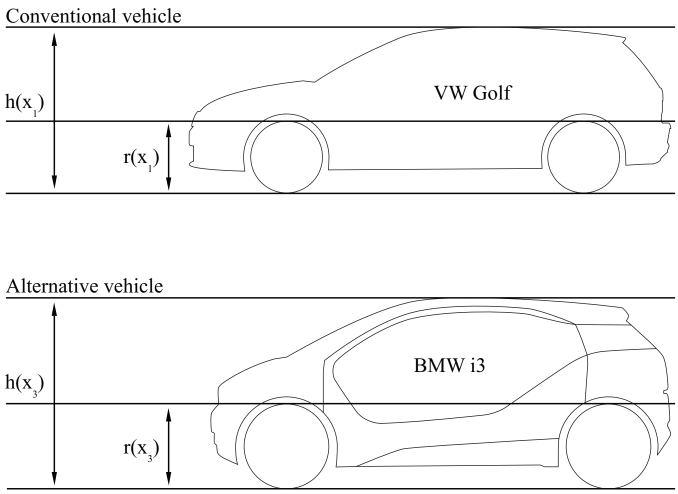

Fig. 5. Comparison between a conventional (x_1) and battery electric (x_3) vehicle.

[1] $\boldsymbol{r(x_1)}$= 205/55 R16 (Golf Comfortline) → 406.4 mm + [(205 * 55%)*2] = 631.9 mm; $\boldsymbol{r(x_3)}$= 155/70 R19 → 482.6 mm + [(155 * 70%)*2] = 699,6 mm

D. Chassis and suspension

Two ways are pursued to overcome the problem of battery storage placement in passenger cars: the adaptation of vehicle architecture, which allows a direct battery exchange service, and the optimization of their integration in car chassis [9]. The Testla S (2013), E segment car, is a good example, Fig. 6. Analyzing the proportions of this vehicle, the following relationships can be defined:

$$b(r) \approx (4 + 1/2)r \tag{8}$$

$$h(r) \approx 2r \tag{9}$$

$$h1(r) < 1/2\ r \tag{10}$$

$$h2(r) < r \tag{11}$$

While (8) fits with the E segment cars, (9), (10), and (11) fit better with the S segment cars [1]. As the thin battery pack is uniformly distributed along the bottom of the chassis, the overall height, the bottom opening door line height, the front lamps, and the bumper height are remarkably low in this car. In terms of performance, the vehicle obtains nearly the same weight distribution on both the front and the rear axles and a remarkably low center of gravity. In terms of exterior proportions, this four-door sedan is comparable to a grand tourer.

E. Body

Fuel cell vehicles try to overcome the problem of recharging by powering their on-board electric motor using hydrogen and atmospheric oxygen as reaction media. The Honda FCX Clarity (2008) is specifically assembled around a fuel-cell engine. Fig. 7 shows a comparison between the FCX and a conventional vehicle of the D market segment (BMW 3 series). For both cars, ***b(r)*** is equal to (8), while ***h(r)*** can be defined as

$$h(r) \approx (2+1/4)r \tag{12}$$

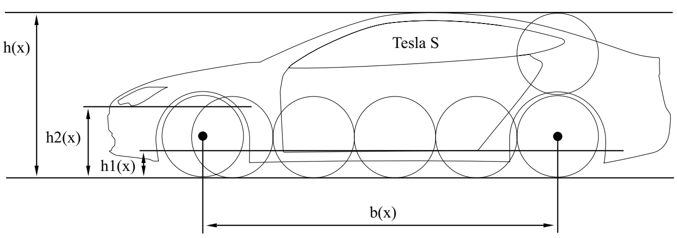

Fig. 6. Exterior proportion analysis of the Testla S.

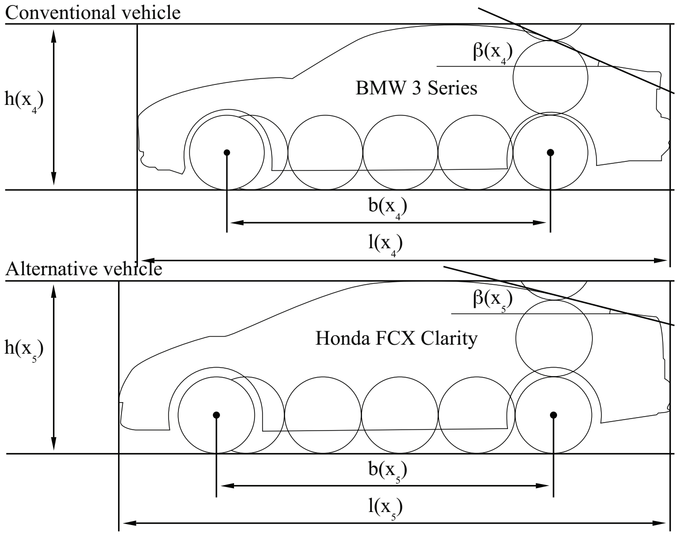

Fig. 7. Comparison between a conventional (x_4) and fuel cell (x_5) vehicle.

Even if the two cars have the same values for ***b(r)*** and ***h(r)*** parameters, the fuel cell vehicle is perceived as not proportioned. The reason is that the rear windshield angle ***β(x₅)*** makes the rear part of the car too high in comparison to the front. It is an effect of the bulky hydrogen fuel tank placed at the back of the car. In fact, the volume of the hydrogen tank needs to be at least four times larger than a full tank of gasoline for an equivalent distance of travel [10].

The battery electric concept MUTE (2011) was designed at the Technical University of Munich and is legally classified in Europe as heavy quadricycle (L7e homologation), Fig. 8. Analyzing the proportions of this mini car, it can be pointed out that ***h(r)*** is equal to (12), while ***b(r)*** can be defined as

$$b(r) \approx (3+3/4)r \tag{13}$$

The segments OA and PC can be considered in order to define the position of the points A and C in respect to the wheel. In this car the drivetrain layout is rear engine and rear wheel drive. ***A*** matches with the point O and ***C*** is positioned to the right of the point P. Thus:

$$A(ERR): A \equiv O \tag{14}$$

$$C(ERR): C > P \tag{15}$$

The small size of this vehicle (***h(x)***=1310 mm; ***l(x)***=3550 mm) does not affect its proportions. The car looks balanced due to the A and C-pillar positioning. The point ***A*** ends close to the center of the front wheel; therefore, because of the distance between front wheels and A-pillar, the viewer perceives the vehicle as more powerful [1]. In addition, the point ***C*** ends right after the center of the rear wheel, thus the body is perceived longer than it is in reality. Despite the size of the MUTE, the interior offers two small luggage compartments:

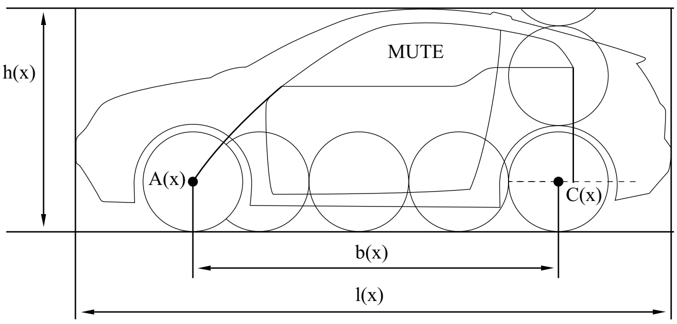

Fig. 8. Exterior proportion analysis of the vehicle concept MUTE.

one is placed at the back of the car, with a large rear trunk lid for easy loading and unloading, and the other one at the front. To make this possible, the engine is placed at the back, right before the rear axle; while the battery pack is positioned right beyond the seats in vertical position. This layout guarantees also an optimal weight distribution in the chassis.

F. Interiors and cargo area

The role of compact light vehicles should grow in the future and, therefore, a new class of vehicles will be needed to combine ultra-light design with an electric or fuel cell engine powertrain. At this regard, a proper aerodynamic shape to compensate the low energy storage capacity of batteries, and car interior space optimization to design new compact vehicle solutions, are essential.

As far as aerodynamic shape design is concerned, the GM battery-electric vehicle EV1 (1996) had a cx coefficient of 0.195. This car was the first mass-produced and purpose-designed electric vehicle of the modern era from a major automaker [11]. Fig. 9 shows the comparison between the GM EV1 and the VW XL1 (2011), the production vehicle with the best cx coefficient on the market (0.189). The older aerodynamic vehicle (x_6) exhibits a ***b(r)*** value similar to (8), while ***h(r)*** is similar to (12). As far as the XL1 (x_7) is concerned, ***h(r)*** is equal to (9), while ***b(r)*** can be defined as

$$b(r) \approx 4r \tag{16}$$

Compared to the EV1, the XL1 is lower ($\boldsymbol{h(x_6)}$=1283 mm; $\boldsymbol{h(x_7)}$=1153 mm), shorter ($\boldsymbol{l(x_6)}$=4310 mm; $\boldsymbol{l(x_7)}$=3888 mm), and reaches exterior vehicle proportions close to a grand tourer [1]. The strive for the lowest drag coefficient reachable shows a serious impact on both cars; in fact, they offer only two seats and a very limited cargo area. This goes against the fact that the car interior space optimization will be a key element in future vehicle design, due to the increase of megacities around the world [12].

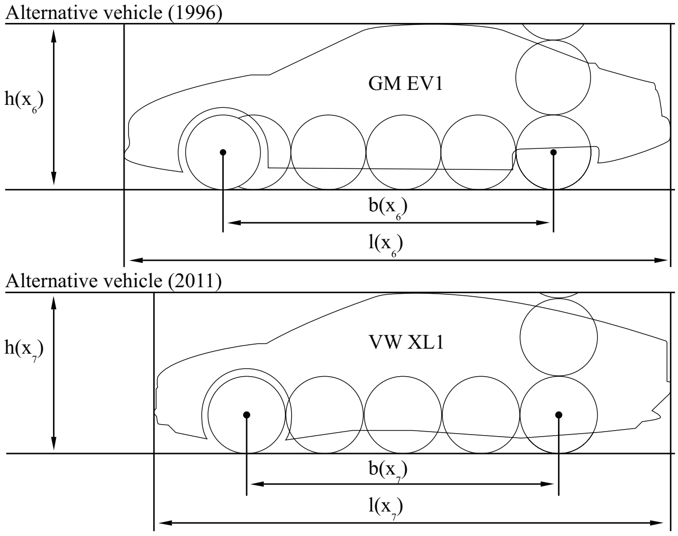

Fig. 9. Comparison between a recent (x_6) and past (x_7) alternative vehicle.

The Rinspeed Micromax (2013) represents a solution in such sense, Fig. 10. This is a battery electric vehicle with an innovative interior space distribution. Three adults and one child find space in the car in addition to the driver. In order to optimize the interior space, the passengers have a semi-standing position, with room left over for an unfolded baby stroller or shopping cart. There is not a fixed space for occupants and cargo area, but rather the possibility to increase the former or the latter according to the usage. The chassis is made of fiber-reinforced thermoplastic composites and is very low to facilitate the access through plexiglass side door windows with a non-scratch coating, like in a bus. For the Rinspeed Micromax ***b(r)*** is equal to (8), while ***h(r)*** can be defined as

$$h(r) \approx (3+1/2)r \tag{17}$$

Even if the overall length of the Rinspeed Micromax is comparable to a mini car (**l(x)**=3730 mm), the shape of this vehicle makes it comparable with a mini-bus (***h(x)***=2200 mm). The typical car proportions of current M1 vehicles are lost, and a new kind of transport system is presented. At this regard, the absence of overhangs in this car suggests the importance of new safety features to compensate the absence of a front crash area [13]. Only further few attempts have been done so far to put new electric vehicle concepts out from scratch into production, as these vehicles often do not meet the current M1 vehicle safety regulations [14].

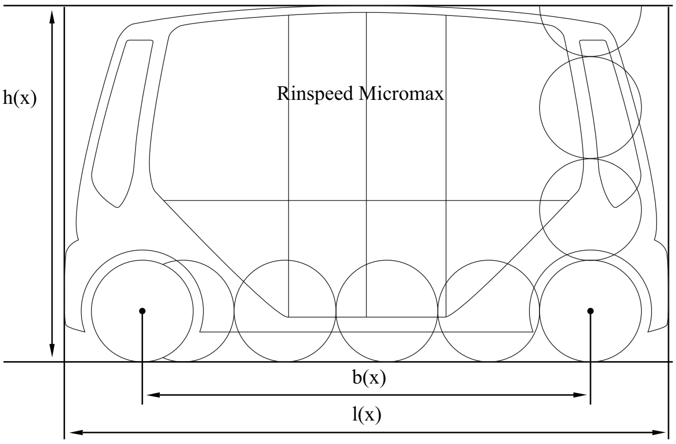

Fig. 10. Exterior proportion analysis of the vehicle concept Rinspeed Micromax.

IV. DISCUSSIONS AND CONCLUSIONS

Chapter III has shown how electric components can influence the overall vehicle package of the current alternative vehicles. The abovementioned mathematical relationships represent a first approach to formally evaluate the impact of electrification on vehicle proportions. These changes can be summarized as follows:

- Due to the placement of the battery in the car underfloor, the wheelbase ***b*** is longer (e.g., GM Volt, Reanult Twizy Z.E., BMW i3, Testla S, Rinspeed Micormax), and the relationship between car body ***d*** and greenhouse ***g*** may appear unusual (e.g. GM Volt). To overcome this problem, some vehicles are lower in respect to the ground: the height of the lower door line ***h1*** (e.g. Testla S, MUTE) and height of the lower point of the front lamps ***h2*** (e.g. Testla S) are lowered. Other vehicles have bigger wheels to reach a better proportion between wheels and the high car body (e.g. BMW i3).
- The majority of internal-combustion engine cars adopt a front engine and font wheel drive (*EFF*) drivetrain configuration, and their A-pillar position often appears to be not proportioned in respect to the whole body; the engine is placed transversally and the front wheels must be placed behind the engine, because the transmission itself is placed behind it. Due to the increasing use of rear engine and rear wheel drive (*ERR*) drivetrain layouts in battery electric cars (e.g. BMW i3, Testla S, MUTE), the distance between front wheels and A pillar can be bigger, and hence better proportioned in respect to the whole body. In some electric vehicles, the point ***C*** ends behind the center of the rear wheel for functional (e.g. Testla S) or aesthetic reasons (e.g. MUTE).
- Changes in the angle of front and rear car windshields due to aerodynamic design (e.g. Toyota Prius, GM VOLT, VW XL1) or to functional reasons (e.g. Honda FCX Clarity) suggest the importance of integrating the front windshield angle $\boldsymbol{\alpha(x)}$ and the rear windshield angle $\boldsymbol{\beta(x)}$ in the key features of Fig. 1.

Even if car technology is changing according to environmental and social issues, the results have shown that car makers design alternative vehicles with certain aesthetic tricks, in order to keep new vehicles similar to conventional ones. Therefore, the innovation potential offered by alternative engines to create specific car architectures is not exploited. Alternative cars become a mere compromise between the aesthetic proportions of conventional vehicles and the additional space needed to fit new components such as the battery.

Some of the most innovative concepts available on the market try to design new compact solutions to accommodate social and environmental changes (e.g. Reanult Twizy Z.E.), or explore new architecture solutions in which interiors and cargo area can be flexibly changed according to user's needs (Rinspeed Micromax). As alternative vehicles need to overcome the low range of batteries, the constant growing of the body height appears to be an issue in respect to their frontal area and their aerodynamic drag coefficient. Car safety is another key point, not only because of the safe integration of new relevant components in car packaging. Trends such as the extension of the wheelbase to gain more space between the axels, could foster innovation in terms of passive and active safety to address the consequent shortening of car overhangs.

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