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Usability heuristics and their role in designing vehicles–A case study of an electric-hybrid vehicle body design

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Abstract

Morphologies for designing vehicles and their bodies traditionally rely on engineering optimization of variables such as strength of materials, structural rigidity, loading characteristics and manufacturing constraints, to name a few. Combined with automotive engineering and ergonomic safety standards such methodologies have limited scope for incorporating user-desired or utility-led innovations, especially during conceptualization. Often local utility-based requirements and usage characteristics conflict with global safety and engineering standards. Resolving such conflicting issues normally results in longer designing cycles. This paper presents through a case study an alternative design conceptualizing morphology based on usability heuristics as practiced in the field of industrial design. Usability heuristics are formulated based on user studies and are used to specify product attributes which are later on developed into physical product features not only from the appearance but also from engineering point of view. This paper attempts to show through the vehicle design case study how usability heuristics can integrate with engineering specifications to form an usability engineering morphology that facilitates reduction in design conceptualization cycle time and simultaneously increase the scope for utility-based innovation.

Keywords: Conceptualization, industrial design, chassis, body design, usability engineering morphology.

1. Introduction

Vehicles are not only products of mass manufacture but also of mass use. ‘Mass’ manufacture reflects vehicle numbers, whereas ‘mass’ use reflects user numbers. Ever since Ford mass-produced the car and made it economically feasible, the quest for refining designing procedures to achieve economically mass-manufactured vehicles for the masses is being pursued by automotive engineers on one hand and industrial designers on the other [1, 2]. Each method of design has its hierarchical procedure and its own structure which when put together represents the design morphology [3]. Till the end of the 90s, design morphologies for products including vehicles were heavily influenced by engineering methods. Globalization of the market has led to increasing focus on the user necessitating change in designing morphologies from the traditional engineering-led to the present customer-focused one [4, 5].

1.1. *Engineering morphologies in vehicle design–an overview*

Traditional morphologies adopted for designing vehicle bodies started with and aimed at optimization of engineering variables such as acting forces, materials, manufacture, and

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costs. Designing started with the parts and ended with the whole. Ever since the 1950s, designing activity concerning the ‘whole’ has been termed as body styling and the ‘parts’ as engineering. Integrating the two into a final vehicle design was the last phase in such linear designing morphologies [1, 2, 6, 7]. For example, in the case of space frame chassis, engineers aim at optimizing engineering variables such as forces due to shock or impact, vibration characteristics, and manufacturing constraints to name a few before adding the ‘cabin’, often as a shell, on to the engineering-certified chassis. Thus the ‘shape’ of the body is ‘styled’ by the so-called styling artist while the ‘shape’ of the chassis is ‘designed’ by the engineer [2–8]. In India, as of present, cabin building is done on drive-away chassis for several types of public vehicles by the unorganized sector with no knowledge of ergonomics, comfort or even the attribute called as ‘style’ [5].

By 1950s, there was a clear division of engineering and styling functions which finds echo even in today’s vehicle design methodology. To a large extent, there has been integration of the engineering and styling specifications as in the case of monocoque body designs. Even in such cases, the relationship between the two specialists remains superficially integrated and uneasy [1–8]. The styling team has always been under the control of engineering, advertising and marketing departments [1, 7–9].

As a result, during conceptualization of a new vehicle, the utility value consisting of usability, comfort and safety are lumped together as ‘looks’ or appearance and are not included as part of the core engineering specifications for the vehicle. The possibility of factors such as ‘user needs’ and ‘usage habits’ driving innovations in engineering are not evident. The perception seems to be that at best they influence taste and appearance matters of the customers and have to be accommodated without disturbing the core practices in engineering design.

Techniques like QFD emerged in the late 80s aiming to convert customer wants/needs into engineering specifications but are largely based on quality issues and value analysis. They are useful as tools for analysis of the so-called market perception [10, 11]. While QFD enables a development team to reach consensus for specifications using tools like House of Quality matrix, the matrix by itself does not generate specifications; it documents them [10, 11]. A customer’s ‘requirement’ need not necessarily translate into ‘customer use’. Mere taking care of the ‘needs’ in terms of being able to convert them into engineering specifications via QFD cannot ensure their transformation into a usable solution unless it undergoes numerous iterations through visualization. At best, usefulness can be derived and specified but ‘useful’ need not necessarily mean ‘usable’. QFD as a visualizing and conceptualizing tool has its limitations for the designer. It is not precise enough for an industrial designer to use in creative visualization and conceptualization of new designs which involves contextual evolution of form and its attributes such as space, utility, construction, strength, cost and appearance to name a few.

Throughout the 80s which saw the emergence of practices such as Concurrent engineering, Systems design and Product Life Cycle Management techniques (PLCM), qualitative factors that make up usability, appearance and comfort, while being recognized for their high sales value, do not find themselves easy to be incorporated within the engineering design specification and processes. Some CAD programs of late have started closing the gaps but are once again heavily dependent on the specialization of the person using those CAD tools.

The only exception in automotive engineering design morphology of vehicle bodies has been the mandatory integration since 1970s of ergonomic safety standards and practices in the conceptualization stage. This happened after motor vehicle safety standards were legislated in 1965 [9]. Ergonomic standards such as SAE J1138, SAE J1517 and others do give guidelines concerning users' safety and comfort but are specific to geographically integrated human races. For example, European or USA ergonomic specifications are not suitable for Indian population or Indian usage habits [5, 12, 13]. To cite a specific instance, dimensions of ingress and egress openings specified by the European/USA population-based ergonomic standards for automobiles have serious consequences when adapted to the Indian women's attire of a free flowing garment like a sari Indian anthropometric data is next to nonexistent [13]. Usability heuristics go beyond adopting useful ergonomic specifications and standards.

Thus, it is posited that existing designing morphologies relaying on inputs from engineering, industrial design or ergonomics, either have limitations for visualizing and conceptualizing design solutions or result in unsatisfactory synthesis of the qualitative and quantitative variables during conceptualizaton. Existing engineering design morphologies seem to continue with the old styling processes [2, 7, 8] which began in 1926 and which are no more relevant in industrial design today given the industrial designers' shift to user-centered design (UCD) [14, 15–17], rather than being dominated by aesthetics alone.

2. Limitations of adopting existing designing practices and standards in the Indian context

Almost all cars on Indian roads have their design origin outside India. Even in the case of indigenous development of one or two cars, Indian automotive engineers and designers rely on designing standards, norms and morphologies being practiced elsewhere [18]. Along with the designing processes, many of the specifications as practiced in the design originating country gets invariably adopted. Most of these are relevant in Indian conditions only if they are applied to the class of vehicles for which they have been evolved originally. For classes of vehicles that do not exist elsewhere, for example, the Indian three-wheeled autorickshaw or the proposed small electric-hybrid vehicle, such adoption of standards/specifications/designing practices may not be locally suitable or feasible and can also become a contentious issue as in the recent case of quadracycles (QC) reported widely in the Indian press [19]. Manufacturers in India intend quadracycles to be extended versions of the autorickshaw but with four wheels. They are reluctant to adopt the European standards for QC (that cap their weight at 600 GVW) as expensive light-weight materials will have to be used for the chassis and body to reduce weight and come up to safety standards. This would make the QCs more expensive than the lowest priced version of the car available to the Indian user. The QC contenders in India state that while the QC is meant for goods transport in Europe, in India it is intended to carry passengers and therefore increase in weight is justified while retaining an open body structure. This is not acceptable to car manufacturers in

Table I
Comparison of a few select specifications for the proposed quadracycle for India and the existing entry-level basic car [19]

Specifications	Proposed QC for India	Basic entry level car
Engine	15 kw 200–250 cc	30 kw 800 cc
Top speed	72.5 km/h	110 km/h
Passengers	4	4
Gross vehicle weight (GVW)	$> 600 < 800$ kg	$> 800 < 1000$ kg

India who insist on applying safety standards uniformly to cars and QCs especially when QCs for India will, if introduced with increased weight (as being proposed by QC manufacturers), closely match the weight of a basic entry-level car thereby blurring the market segments (Table I). Thus, adopting standards and specifications from elsewhere becomes contentious. Standards, specifications and processes, instead of encouraging new morphologies and innovations in the local context, are likely to become protective boundaries for market segments. Vehicles such as autorickshaws and small electric–hybrid three wheelers for use in India need to generate contextual design specifications based on local use factors if they have to compete with existing vehicles and segments whose standards and designs originate elsewhere.

2.1. *Generating contextual specifications for electric-hybrid three wheeler: a case study*

A feasibility study [20] was done to ascertain the magnitude of the problem, technical requirements to be fulfilled and the extent of similarity to the present autorickshaw, of the proposed hybrid-electric-hybrid vehicle (EHV). The study started with the assumption that if the current autorickshaw is suitable for conversion into an electric vehicle, it will also be a feasible candidate for an electric-hybrid conversion later. A user survey consisting of ethnographic study and documentation of use patterns, interviews with the autorickshaw passengers and drivers yielded usage information that was used to frame the design heuristics for the new vehicle which also acted as qualitative specifications for the industrial designer. To estimate the form factor consisting of size, weight, shape and aesthetics, calculations were done to find out the most feasible set of batteries, motors, drives, chassis materials and manufacturing practices. Since batteries influence the form factor to a large extent, only their data has been reproduced in Table II from the detailed study report [20].

The most widely used batteries, namely, lead acid type, six in numbers, provide an effective range of 95 km, their total weight being 150 kg (Table II). Other batteries were ruled out due to cost and availability factors in the Indian context. On the other hand, for an Indian city like Bangalore, a range of at least 200 km per day is desirable with one time charging as deduced from the user study [20]. In order to achieve this range, doubling the batteries from 6 to 12 will not only increase the size to one and a half times of the present 600 kg autorickshaw but also make it much heavier. In such an event the total weight of the vehicle, along with the batteries, is likely to be well over 800 kg. This increased weight

Table II
Calculation of range estimates for different types of batteries for a 600-kg vehicle

Battery type	Volts	Nominal capacity (Amp h)	Total nos	W h battery	W h total (Wh)	Cruising speed on zero slope (km/h)	Power at motor (W)	Life of battery at 80% discharge (h)	Effective range (km)	Battery life (cycles)
Sodium nickel chloride	12	105	6	1260	7560	30	1270	4.7	200	1000
Lithium ion	12	90	6	1080	6480	30	1270	4	170	1000
Nickel metal hydride	12	80	6	960	5760	30	1270	3.6	152	2000
Lead acid	12	50	6	600	3600	30	1270	2.2	95	1000

brings the proposed electric vehicle closer in category to the existing entry-level car segment in the market similar to what is shown in Table I. Narrowing of categories can lead to a situation wherein new technologies such as electric and EHV seem to become economically unviable to the user, in comparison to IC engine technology, despite the environmental advantage and benefit of low emission. Rather than trying to fit in between existing segments and having to adopt their specifications and standards that go with such segmentation, choosing new ‘use’ niches requiring smaller vehicles and having an operating range limited to 100 km will make the electric technology contextually viable. New niches such as exhibition grounds, police beat vehicles, point-to-point campus vehicles, etc. were identified and suggested after conducting a niche study [20]. For such new niches, not all specifications for the chassis and body can be adopted from the existing automotive engineering norms and standards. Rather, these have to be derived from the context of use.

The viability in terms of performance parameters like range, cost, etc. of such a niche-specific electric vehicle can be further improved by converting it from an electric-driven to an electric hybrid. Such an EHV can then be adapted to any other new or existing segment and compete on its own technology strength. In the electric-hybrid concept, with an addition of onboard small-capacity IC engine or natural gas-driven generator, the batteries can be charged at will thereby eliminating the ‘range’ constraints so characteristic of ‘electric only’ vehicles. Further, the increase in size, volume and weight due to batteries necessitated by range specifications in pure electric vehicles need not be a constraint in EHVs, as the number of batteries can be determined contextual to the situation. The industrial designer will therefore have fewer engineering constraints for specifying and conceptualizing form factors in EHVs. Based on this inference, a set of three chassis and body designs were conceptualized for the electric-hybrid three wheeler.

3. Usability engineering approach adopted for conceptualization of the hybrid-electric three wheelers

Since existing specifications and standards were of limited assistance, a design morphology starting from the users’ end was experimented with and continuously evolved. A series of three new designs of the body and chassis of a hybrid-electric three wheeler was finalized after numerous trail concepts. Table III shows the details of the three final designs. Design 1

(Fig. 1) with one wheel in the front and two in the back in the classic autorickshaw configuration is meant for use niches such as ‘point-to-point’ and ‘campus transport’. It can also be adopted as an electric-hybrid public autorickshaw vehicle. Design 2 is a variation of Design 1. Design 3 (Fig. 2) with two wheels in the front and one in the back is intended for enclosed tourist circuits such as historical ruins, outdoor display parks, exhibition grounds, etc. Design 3 provides larger cabin space, outdoor viewing area, and is more stable due to its two front wheel configuration. All three designs finally selected are of almost similar dimensions but with different form factors and use function.

Table III
Specifications of the three new designs

Specifications	Design 1 LP3W 1 One wheel in front. Curved face model.	Design 2 LP3W2 One wheel in front Straight face model.	Design 3 LP3W3. Two wheels in front. Broad face model.
			
Overall dimensions	1.340 W × 2.89 L × 2.10 H (m)	1.71 W × 2.69 L × 1.92 H (m)	1.39 W × 2.76 L × 2.17 H (m)
Ground clearance	0.20 m	0.20 m	0.20 m
Wheel track	1.25 m	1.22 m	1.25 m
Wheel base:	2.0 m	2.0 m	2.17 m
Maximum weight: (Unladen) for			
a) All MS (including body panels)	1008 kg	1217 kg	1730 kg
b) MS + ABS parts	600 kg	771 kg	760 kg
c) MS + aluminum panels	695 kg	785 kg	950 kg
d) All aluminum	595 kg	607 kg	706 kg
e) Aluminum + ABS	500 kg	502 kg	513 kg
Dead load	50 kg	50 kg	50 kg
Live load (Passengers)	240 kg	240 kg	240 kg
Max payload	290 kg	290 kg	290 kg
Ingress/egress	Straight–2 stepped	Straight–2 stepped	Straight–2 stepped
Position of CG (H) (with live load)	0, 55 m from ground	0.51 m from ground	0.62 m from ground
Passenger configuration	1F+2B	1F+2B	2F+2B
Total power (KW)	5 kW @ motor	5 kW @motor	5 kW@motor
Range	Limitless	Limitless	Limitless
Battery only, range	40 km	40 km	40 km
Motor	AC-induction	AC-induction	AC-induction
Controller	Pulse width modulation	Pulse width modulation	Pulse width modulation
Breaking regeneration	2 to 3%-Regenerative	2 to 3%-Regenerative	2 to 3%-Regenerative
Batteries (26 kg each)	Lead acid, 12 V20AMP × 12	Lead acid, 12V20AMP × 12	Lead acid, 12V20AMP × 12
Engine–Generator (Honda EU30IS)	196 CC, IC	196 CC, IC	196 CC, IC
Fuel	Petrol/gas	Petrol/gas	Petrol/gas

FIG. 1. Scaled model of Design 1.

FIG. 2. Scaled model of Design 3.

Though much of the current research in usability being reported extensively is on software and information technology products concerning human–computer interactions (HCI) [21, 22–24], user-centered design and usability have been one of the core concepts of industrial design since 1970s [15, 16, 25, 26]. The ISO 9241 which is applicable to both software as well as physical products defines usability as follows: The extent to which a product can be used by a specified set of users to achieve specified effectiveness, efficiency and satisfaction in specified context of use. The emphasis on the word 'specified' in the ISO definition of usability is to be noted. Both qualitative as well as quantitative attributes need to be specified wherever human beings are involved. Just because some of the qualitative aspects of products cannot be defined in terms of dimensions and metrics as in conventional engineering does not necessarily exclude them from being called specifications.

The user-centered design method is governed by four fundamental axioms of design [27], namely: (a) User is the only constant entity of a system under design; (b) User is the starting point for all design conceptualization processes; (c) User is the final datum of reference for all design decisions, and (d) User is the measure of all things. The three concepts of electric-hybrid vehicles shown in Table III are the outcome of usability (as defined in ISO 9241)-based specifying and designing processes. The sequence of the stages, issues, tasks and output of the processes used in conceptualization are shown in Table IV. The last column of Table IV, labelled as usability engineering morphology, depicts comprehensively the entire sequence that was followed in the case study. A detailed description and treatment of the usability-centered design processes that was undertaken is beyond the limited space within Table IV. It is intended to illustrate an overview of the processes that resulted in morphology. Table V attempts to show some of the underlying processes especially those of design specification generation, mapping of attributes to features and their synthesis during conceptualization. Both qualitative as well as quantitative engineering features are synthesized during conceptualization and are visualized as models. Some of the differences between the traditional engineering and the usability morphologies are attempted in Table VI. The qualitative attributes of body and chassis are optimized without conflicting with optimization of quantitative attributes. Neither the qualitative nor quantitative attrib-

Table IV
Processes involved in formulating a usability engineering morphology

Processes	Issues	Tasks	Outputs	Usability engineering morphology
(1)	(2)	(3)	(4)	(5)
User identification	Who are the likely users?	Market segmentation studies and factorial analysis	Niches that have the “best fit to requirements” that an EV3W can serve have been identified	Defining and understanding user ⇩
Study of context of use	How do current users of three wheelers perceive it. What problems do they have? What are the habits, usage patterns, and abuses/misuses? What is the nature of experiences?	Heuristic evaluation of passengers and drivers involving ethnographic observation and protocol analysis	Problems identified. Experiences recorded. Desires, expectations documented. Figs 6–8	Contextual investigations ⇩
User’s mental model formation	What the user wants. What type of experience needs to be incorporated?	Interviews observations dialogues	Attributes of the proposed design.	Perceptual modeling ⇩
Specification generation	What qualitative and quantitative inputs the designer and the engineers want	Study and extraction from legal, engineering and local practice (cultural norms)	Industrial design specifications of the vehicle. Engineering specifications of the vehicle including subsystems.	Specifications ⇩
Conceptualization Designer’s mental model of the user’s mental model.	Creating a new vehicle to fit users mental model within engineering constraints.	Semantic analysis, alternative anatomy configurations. Whetting engineering constraints. Building all features as per specifications. Simulations and modeling. Computer-aided designing.	Sketches, 3D study models, ergonomic profiles. Assembly drawings for structure. Layout and anatomy alternatives in the form of technical drawings.	Visualization and conceptualization ⇩
Experiments and simulation studies including product engineering.	Which of the conceptualized designs to choose from? How can the designs be validated. How to detail out the features. How best to manufacture the parts. Cost/Engng analysis. Feasibility analysis.	Evaluation and auditing of the designs. Ergonomic rigs and 1:1 profile testing to validate experience of space and layout configuration. FEM analysis for structural integrity. Safety audit.	Final concepts. Technical drawings. Ergonomic specs. Material specs. Costing. CAD files. FEM analysis of structure for engineering strength and crash safety.	Industrial design and engineering validation ⇩

Contd…

Table IV *Contd…*

(1)	(2)	(3)	(4)	(5)
Simulation, modeling and prototyping of test rig.	Information for prototype building. Information for design for manufacture. Information for detailed engineering design of parts and components.	Building scaled models. Building 1:1 full scale display and user experience feedback model. Validating total design. Inputs to building and testing prototype. Inputs to tooling and production design team. (Future).	Design as desired by the ultimate user; as specified by the context of use and as per engineering requirements. The final designs are in compliance with ISO 9241.	Prototyping and testing ⇩ To detailed design for manufacture

utes had to be subservient to each other, nor had they to be approached linearly while converting attributes into features and engineering them physically.

Monocoque designs also achieve such optimization but are found to be economically unviable for low-volume manufacture especially in the case of small EHVs meant for dedicated use niches such as exhibition grounds and tourist circuits. The need to adopt local manufacturing processes for the EHV under case study in this paper discounted exploring monocoque designs.

3.1. *Formulating design specifications and their synthesis during conceptualization*

The transformation of attributes to features, as depicted in Table V, is an objective account of the visualization processes done by the designer during which the users' mental model is synthesized with the designer's mental model to conceptualize the final design solution. This transformation is one of the important characteristics of the usability design morphology depicted and distinguishes it from other traditional engineering and traditional 'looks' or 'style'-oriented industrial design morphology. It is at this stage that the qualitative and the quantitative requirements are innovatively synthesized by the designer. A detailed description and treatment of the entire usability-centered design process for all the three designs are beyond the scope of this paper. However, an attempt is made here to bring forth select aspects of the two conflicting situations between attributes and features including their resolution by synthesis at the concept stage itself.

3.2 *Resolution by synthesizing quantitative and qualitative aspects within the design space*

The EHV had to be conceptualized such that the safety, comfort and geometry which defined the product's physiography [27, 28]; the layout, structural rigidity, assembly, scale of production–all of which defined the product's anatomy [27, 28], resulted in the products physiognomy [27, 28]. Physiognomy defines the vehicle's distinct visual looks and semantics. An industrial designer aims at synthesis between physiography, physiognomy and anatomy of the product during the act of mental visualization. Table V shows the overview of these relationships using which the final concepts manifested from the visualization.

Specifications and standards being followed for passenger cars cannot be adopted to conceptualize the niche-specific EHV which had to be smaller in size, lighter in weight, appro-

Table V
Usability factors. Their transformation into features starting from the design space and ending as three final design concepts via visualization

Design space of the proposed EHV three wheeler	UE factors leading to total user's experience	Corresponding desirable product attributes condensed from user expectations and desired experiences	Proposed features, as conceived by the industrial designer, to reflect attributes
PHYSIOGONOMY	Visual quality Semantics	Appearance should be in consonance with new designs seen in current imported cars on the road. It should definitely be better than the current autorickshaw. Should depict modernity and progress. Inviting appearance. Communicating, safety, comfort, quick, smooth, noiseless ride as in a car/taxi. Respect and take good care of the passenger. Make the passenger feel important and worthy. Soft service with a smile. Ride must be panoramic and enjoyable. Feeling of assurance and safety.	Form: Geometric and organic Nature: Youthful. Form transitions: Sharp between sub forms and gradual on total form. Visual metaphor: Digital to reflect energy efficiency of the electronic systems inside. Boundary and edge conditions: Medium to sharp radii to evoke emotions triggered by *Veera+Hasya+Shringara rasas.* Semantics: Cocoon-like enclosed protective space. Sign: Cradle or easy chair. Meta sign (cultural): Royal Palki
PHYSIOGRAPHY	Safety Comfort Utility	Protect drivers and passengers against injury. Better lighting. Larger interior space for both the driver and the passenger. Better operability and functionality for the driver in comparison to the autorickshaw. Deeper and higher seating area for the passenger. Clean, pollution-free cabin boarding sitting and alighting to be natural and exertion free. Wide entry area. Provision for providing commuter information and entertainment.	Error- and accident-free use by ergonomic design. Drivers console to be personalized by better layout of dash board. Passenger cabin to be 'enclosed' providing semi-privacy, all round visibility and ride comfort. Transparent pull down blinds. Acoustic treatment of interiors to absorb sound. Ingress to be inviting. More utilitarian passenger amenities such as fare meter, GPS, to be included. Split-level steps for entry/exit. Built-in infotainment panel for passengers. Protective safety fenders on all sides. Forced ventilation of cabin by design of pressurized air flow.
ANATOMY	Layout configuration Structural rigidity Materials Scale of manufacturing	Maximization of interior space. Seating and storage configuration to largely follow current three wheelers. Larger diameter of wheels. Protect driver and passenger from frontal collusions. Capable of localized repair and maintenance. Light-weight materials preferred. Use of recyclable materials. Routine maintenance capability by one person. Not be easily susceptible to dents scratches, etc. in dense traffic. Batch production.	Footprint to be similar to current autorickshaw. Height of platform to be increased to get larger road clearance and side impact protection. Interior height of cabin to be increased. Minimum or nil intrusion of sub-units such as engine, battery, etc. into the cabin space. Rigid chassis structure with frontal crash absorption zone. All round fender/guard protection for body and occupants.

Table VI
Comparisons between the morphologies

Traditional engineering	Traditional industrial design	Usability engineering
Market needs defined by the marketing group	Market needs, tastes/trends as briefed by management.	User needs as researched by designer through contextual investigations along with the brief given by marketing group.
⇩	⇩	⇩
Technical specifications	Style–looks as decided by the designer	Specify qualitative as well as quantitative requirements using usability heuristics and standards
⇩	⇩	⇩
Structure–chassis body–ergonomics	Validate form factor by getting approval from structural-chassis specialist	Visualize concepts by integrating design spaces
⇩	⇩	⇩
Improve appearance without changing anything above as decided by the engineer	Build models with interiors considering ergonomics	Validate concepts through engineering analysis, simulation, user testing.
⇩	⇩	⇩
To detail design	Hand over technical drawings to engineering designers for detailing	Join detailing team with inputs

priate to the context in looks, performance and function. Besides, safety norms for cars such as those under consideration of UNECE-WP 29 [29], if adopted, would require that the proposed vehicle should pass the frontal impact test at 64 km/h into a 1 m, offset barrier of deformable honeycomb structure to simulate off-centre head-on collusion. It should also pass a side impact test conducted at 50 km/h and also a pole test at 29 km/h to simulate running into a lamp post. In addition, it should also clear the pedestrian hit test at 40 km/h. While achieving these would be desirable, such crash test criteria may not be suitable or applicable given the Indian road conditions, traffic behavior, cruising speeds and usage. Even regulation number 52, for small capacity public vehicles, under discussion in UNECE-WP 29 [29] would be inappropriate. For instance, results (Fig. 3) for a Bangalore city drive cycle experiment conducted for the project [30] for 45-min duration on a busy main road indicates 36 stops and starts from zero velocity due to traffic conditions. As seen in the graph (Fig. 3) cruising speeds above 35 km/h could hardly be maintained for any satisfactory length of travel. For the identified niches such as tourist circuits, point-to-point and other niches, the vehicle under design will have cruising speed estimates of about 25 km/h. Therefore, assuming data of drive cycles as in Fig. 3 may be too stringent for enclosed spaces such as exhibition and tourist circuits. Further, adopting safety norms prescribed elsewhere like in Europe [31] or the proposed UNECE-WP 29 [29] would be unsuitable given the enclosed environments such as campuses and exhibition grounds. Yet safety features against frontal crash had to be incorporated within the small footprint area and small wheel base of the proposed EHV design. Solutions like crumple zones in the front and back were ruled out due to increase in the size and weight of the vehicle. Standard ways of incorporating safety were in conflict with the size and weight constraints. Such conflicts and timeframes to adopt ECE standards are already being debated in India by the Society for Indian Automobile Manufacturers (SIAM) [32].

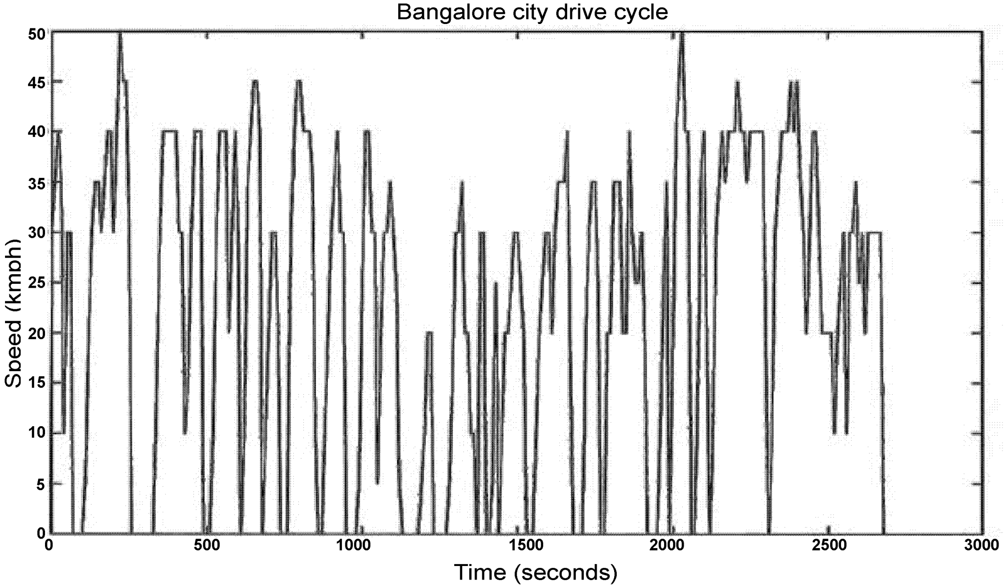

FIG. 3. Drive cycle graph for Bangalore city.

The above conflict between the design space attributes of anatomy, physiography and physiognomy in the EVH under conceptualization was resolved by visualizing the chassis framed structure in a bow shape (Design 1) to make it behave as a shock-absorbing spring in tension (Figs 4 and 5). By doing so, synthesis was achieved both in qualitative attributes such as form as well as quantitative attributes of safety, size and structural rigidity. An elementary finite-element analysis (FEM) analysis of the concept structure was done to ascertain the initial feasibility of the concept, leaving a more in-depth structural analysis for the future. The FEM analysis of all the three chassis was done by two independent teams [30, 33], assuming frames to be beams with different cross-sections for two materials, namely,

FIG. 4. Bow-shaped structural frame.

FIG. 5. Frame integrated with the body.

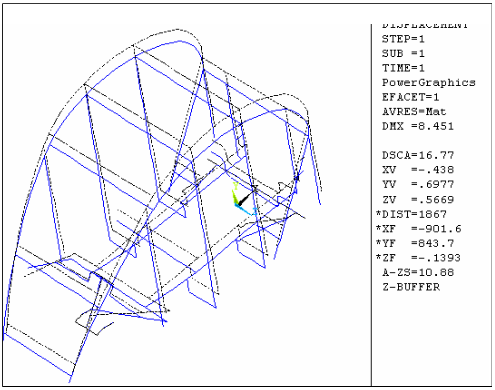

FIG. 6. FEMA. Deformed shape of frame–Design 1.

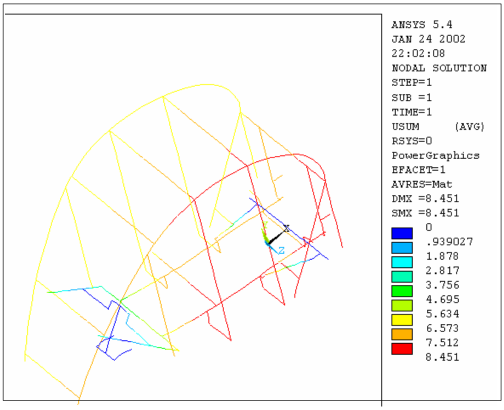

FIG. 7. Resultant deflection for static load of 500 kg.

steel and aluminum. Boundary conditions consisted of static loading through CGs of individual parts with constraints applied to wheel locations. Figures 6 and 7 show a 500-kg loading case for Design 1 with aluminum frames. Figures 8 and 9 show the stress distribution in the frame and its integration with the body for Design 3. Based on the elementary FEM analysis, the chassis was refined further by increasing the cross-section of the structural members and repositioning them to take care of large deflection values at certain weak spots. Innovative additional dampers and shock absorbers (Figs 10 and 11) were also suggested to be integrated for Design 2 chassis. Thus, a conflicting requirement of incorporating crash safety, within the available small footprint area in the vehicle, was resolved by innovative synthesis of the structure and form at the concept stage itself without having to compromise on appearance, size and weight. As mentioned earlier, only a simple static analysis was done mainly to validate the concept which accommodated two conflicting attributes. Had this initial validation not been done, the form factor in the concept itself would be unacceptable to engineers on the team for further attention and would have been discarded with a possible note such as ‘good styling but not technically feasible’.

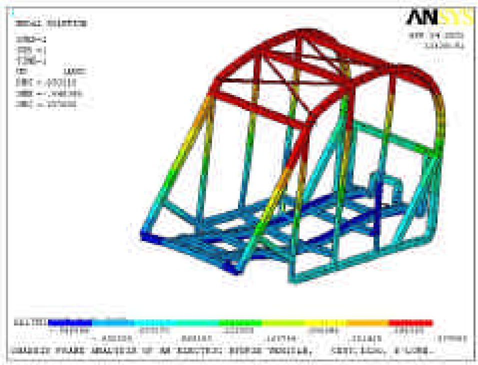

FIG. 8. Stress distributions on Design 3.

FIG. 9. Frame integrated into body for Design 3.

FIG. 10. Chassis with crash bumpers for Design 2.

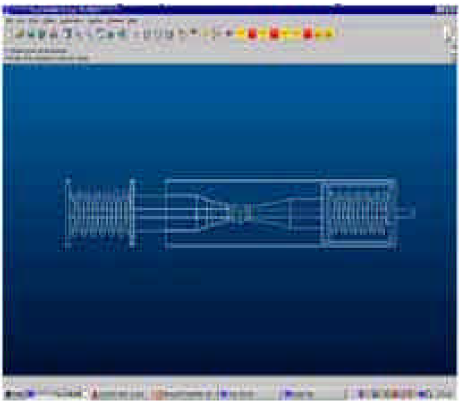

FIG. 11. Bumper cross-section showing plunger with two-stage damping for low and high impact situations for Design 2.

Another conflict between optimization of the ingress–egress opening, as required by the Indian user on the one hand and location of a side impact bar on the other, was resolved innovatively by raising the floor height of the passenger seating area and providing a bumper all around the lower body so as to absorb side impact forces at low speeds. (Design 2 in Table II). However, raising the cabin floor height resulted in a higher CG making the concept unstable. This was once again resolved by relocating the batteries and redistributing other loads to achieve lower CG (Fig. 12).

Thus user-focused safety and other requirements had to be innovated into the chassis and body by synthesis at the conceptulization stage itself. Traditional industrial design morphology would first give precedence to appearance and then wait for clearance from structural engineers often involving more iterations and therefore longer design cycles. Generating ‘use’-based specifications (Table II) and engineering the usability attributes in terms of physical features (Table IV) resulted in the EHV designs shown in Table II. By adopting usability-based engineering morphology both qualitative and quantitative factors can be integrated at the conceptualization stage itself rather than being linearly incorporated at the end during the designing processes.

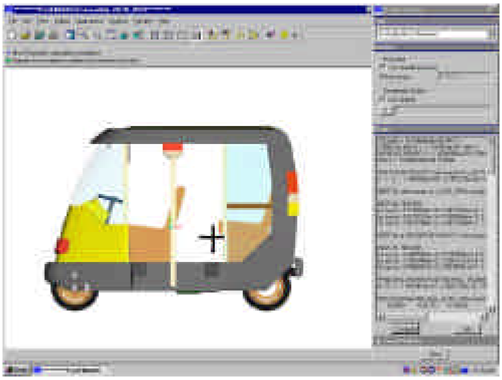

FIG. 12. CG location (marked as +) using CAD simulation for Design 2.

4. Conclusions

Usability heuristics provide a framework for design morphology dictated by the user's needs, perceptions, expectations and usage habits. This morphology opens up more opportunities for innovative design synthesis at the concept stage itself as compared to traditional 'appearance'-dominated industrial design morphologies and the 'standards-optimization'-driven engineering design morphologies. These opportunities in usability morphology can aid the industrial designer to go beyond innovation possibilities provided by the narrow band of engineering optimization, at the visualization and conceptualization phase itself.

Usability morphology and the resulting engineering solutions provide a possibility to manage situations in design wherein solutions that optimize goals of one attribute coming into conflict with optimization objectives of another attribute can be resolved. By synthesizing qualitative and quantitative requirements at the concept stage itself, usability-based design morphology provides possibilities to shorten design iteration cycles.

From the case study it was observed that usability engineering morphology encourages greater innovation during conceptualization than other morphologies that have a tendency to reject a concept based on opinions formed by first impressions and influenced by engineering specifications. When specifications derived from universal standards are not appropriate and relevant in the local context as was seen in the EHV case study, usability engineering morphology can aid in generating contextual specifications.

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