Developing the HMI of Electric Vehicles

On the Necessity of a Broader Understanding of Automotive User Interface Engineering

Christian Knoll[1], Roman Vilimek[2], and Inken Schulze[2]

[1] BMW Group, User Interface Concept BMW i
[2] BMW Group, Concept Quality, Munich, Germany
{christian.m.knoll,roman.vilimek,inken.schulze}@bmw.de

Abstract. BMW i, as a sub-brand of the BMW Group, targets on delivering sustainable solutions for individual mobility. One of the most important steps on this path was the introduction of the all-electric BMW i3 in 2013. In order to design not only the vehicle in itself, but also especially the newly developed electric vehicle related functions for optimal customer experience, the HMI design process substantially relied on repeated usability testing and large international field trials. With more than 34 million test kilometers absolved during the MINI E and the BMW ActiveE field trials an extraordinary knowledge base about customer needs related to e-mobility contributed valuable input to the development of the user interface of the BMW i3 and HMI challenges beyond the vehicle like charging wallbox, smartphone app and web portal related to driving electric.The paper reports on the unique process of defining the user interface of the BMW Group's first purpose-designed electric vehicle including the non-vehicle-based e-mobility infrastructure components. Based on selected use cases, the interplay between evolutionary steps in the HMI and continued usability testing shows how user-centered design is applied for a completely new kind of vehicle, thus providing insights on the necessities of iterative testing for disruptive innovations.

Keywords:MINI E, BMW ActiveE, BMW i3, BMW i, user interface, HMI, ConnectedDrive, 360° Electric, BMW iRemote App, web portal, wallbox Pure & Pro, charge, AC, DC, car sharing, DriveNow, ChargeNow, eDRIVE.

1 BMW i3: Design Background

The BMW i3 is not just another car in the portfolio of the BMW Group. It is the pioneer to a new era of electric mobility and represents the BMW Group's first purpose-built and volume-produced model driven purely by electric power. Some important characteristics which strongly influence the development of the user interface are:

- A new LifeDrive vehicle architecture with the battery pack housed in the aluminium drive module and a lightweight carbon fibre life cell on top. This design provides a spacious passenger cabin with an even floor free of obstacles and *no constructive separations* between the passengers.

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- BMW eDrive hybrid synchronous powertrain developed specifically for the BMW i3, maximum output: 125 kW/170 hp, peak torque: 250 Nm (184 lb-ft) which results in an unusually *silent* yet powerful propulsion.
- Extremely ambitious sustainability targets (concerning production: 70% less water consumption, 50% less energy consumption covered by 100% renewable energy) which lead to an exceptionally high proportion of naturally treated, recycled, and renewable raw materials. This creates a *puristic* interior which resembles more a lounge than a cockpit.
- A built-in SIM card as standard equipment which allows *permanent connectivity* with the BMW backend server. Thus, highly demanding user requests can be processed outside the car (like e.g. real time intermodal routing) and the result of the calculation is then sent back into the car. On the other hand, the user can always stay in contact with the car from anywhere in the world.
- A minimalistic project approach: The BMW i3 is designed for a range of 130-160 km because after years of field tests we know that this provides a fully adequate autonomy for more than 90% of all mobility demands involving a car of that-size[1]. In order to fulfill the sustainability and efficiency targets this means that *efficiency information* concerning range, how to optimize it and how to avoid waste of energy becomes crucial. It also means that *minimalism* or as we call it "clever simplicity" must be the guideline for the overall user interface. It also means *weight* plays a crucial role and every LED, every button and every cable would have to be justified.
- Yet a holistic project approach which offers not just the car, but anything else a user, leaser, or owner of the car might need: From a green electricity contract to a solar car port, from a ChargeNow RFID card which allows charging at most European public charging stations towallboxes for faster home charging, from a smartphone app for Apple and Android devices (BMW iRemote App) to a relaunched-ConnectedDrive web portal which allows to change car settings, share information with other users and stay informed if anything happens which can potentially influence the disposability of the car. To sum it up, when we speak about the user interface, we do not only mean the car but *all* these*touchpoints*.
- And last but not least the pursuit of globally addressing *new user groups* who either do not own a car at all or just use one occasionally, who are not technically minded and do not have experience with BMW interaction principles.

2 Development Process

The aspects mentioned above only form a subset of constraints and objectives. They were enriched by a large set of product requirements defining the story of the car and its functionality. But it is important to mention that the development process was not linear. As e-mobility is a comparatively young field of intense research and development, the initial set of requirements kept changing, too. As for example drive train and battery proceeded, new constraints and requirements came up, leading to a constant discussion on where the boundaries of customer relevance lie. At the same time

not only the BMW engineers kept learning, but also the global legislation and homologation landscape was and still is subject to drastic changes.

Thereby, an important reference point for development was the idea of a minimalistic car which is part of a larger, sustainable, and premium quality mobility system and which emphasizes the aspect of sharing the drive with others. Another was the target to form a user interface which is clever (meaning: offering adequate solutions for the user) yet as simple as possible (meaning: less features and buttons and knobs, low number of alternatives provided, few interaction steps, clear priority of information). These references helped to define two initial UI foundations:

1. The so-called **basic layout** which determines position and distribution of all controls and displays in the cabin
2. The **size of the displays** which clarifies the informatory focal points

Working on these two lead to a set of more specific requirements:

- In contrast to other BMW motorcars, the cockpit should not provide driver-orientation – neither physically nor in terms of informatory exclusiveness. Only those controls and displays *essentially* needed for driving should be grouped around the steering wheel and designed in a highly minimalistic manner. Instead, emphasis should be put on information which is relevant and accessible for all passengers in the car. The result is a cluster instrument which is formed by a 5,8" LCD screen with additional tell tales, accompanied by a 10,2" center display for all navigation, ConnectedDrive, infotainment, communication, and setup functions ("iDrive") as standard equipment.
- To fulfill the functional grouping of drive functions and to allow a much more flexible usage of the interior space the gear selector needs to be moved from its typical position between the front seats to the steering wheel area.
- As the whole startup and driving is silent, appropriate feedback must be provided to ensure mode awareness.
- The so-called one-pedal-feeling which is applied in MINI E and BMW ActiveE must be preserved and improved. This means that lifting the foot from the drive pedal activates a regenerative braking which decelerates the car to a full standstill. At the same time solutions for easy maneuvering in tight spaces and on slopes – fulfilled by idle creep on conventional combustion cars with automatic gearboxes – must be found.
- The fact that the car needs to be charged brings a totally new activity to the majority of users. So the overall procedure in terms of ease of use, cable stowing and handling, feedback, controllability etc must be highly user friendly and inviting.
- As we could also learn from an extensive social media analysis and from years of MINI E and BMW ActiveE field tests, detailed information must be provided on how to drive efficiently and thus maximize range. Hereby maximum advantage should be drawn from the built-in connectivity.
- Car, smartphone app, and web portal must work togetherseamlessly and speak the same "language". Also its aesthetic structure should form a clear link to the BMW i brand.

The iterative development process included the following phases, including a constant monitoring of social media postings and testing of competitor's cars.

1. Initial ideation, utilizing key findings of MINI E field studies.
2. Construction of a functional mock-up with simulated displays.
3. Mock-up usability testing (in a static driving simulator). Focus: Cluster instrument layout, air conditioning controls, and gear selector.
4. Development and testing of the BMW ActiveE UI especially focusing on newly developed EV specific functions as pre-production versions of the BMW i3.
5. Construction of a fully roadworthy prototype (called "I/0ne") on technical basis MINI E with fully integrated simulation of system behavior, demonstrating the full interior, exterior, and smart phone app UI.
6. I/0ne usability testing (on test track).
7. I/0ne usability testing (on test track) of the redesigned overall UI.
8. Usability tests of smartphone app and wallbox professionalUI.
9. Cross cultural usability testing with BMW dealers from US and China and J.D. Power representatives from ECE, US, and China.

The following chapters point out some highlights which might serve as good examples to illustrate how the above mentioned requirements and objectives were finally united into one concept. All examples show the ECE / German UI. US and China UI can differ.

3 Highlights of the BMW i3 UI

3.1 Cluster Instrument

The cluster instrument is the driver's primary source of information and as such plays an important role in reflecting the whole story of the car. In case of the BMW i3 that was an extremely challenging task because from a company's perspective it is not easy to quit with the design paradigm of driver orientation and to abandon its iconic, brand shaping center instrument (Fig. 1).

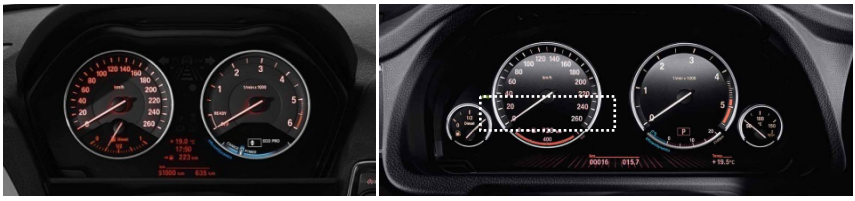

Fig. 1. BMW heritage (Fotocredit: BMW Group): The current "two eyes" (F20 1 series, left / A0161657) and "four eyes" (F10 5 series, right / A0173684) cluster instruments. Dotted line (right) indicates the display size of the BMW i3 cluster instrument display in comparison.

The display of the BMW i3 cluster instrument (Fig. 2) bears all basic driving information – such as speed, range, drive train info etc. Because of the minimalism design requirements this display measures half of the display area in the 5 series

cluster instrument depicted in Fig. 1 – and the 5 series instrument is additionally equipped with four analogue pointer instruments [2]. It is obvious that this ambitious target size required a radical reduction of information both in terms of quantity and complexity.

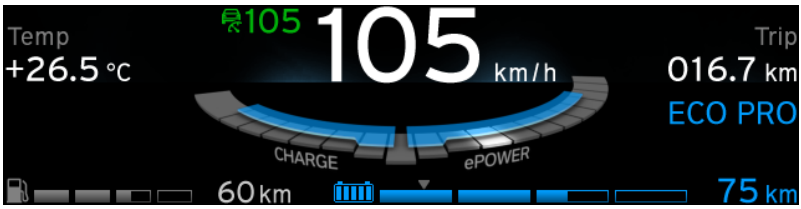

Fig. 2. Cluster Instrument BMW i3 (Fotocredit: BMW Group): Display area with current speed, drive train gauge, fill levels andranges for petrol (range extender version) and battery. Top left on board computer (toggle). Top right Trip. Green speed indication: Current speed = ACC or DCC resume speed. ECO PRO: Current mode).

First thing to be eliminated was the analogue speedometer. It has doubtlessly clear advantages when it comes to quantitative judgment and the perception of disproportionally varying values [3]. But in the context of a car for metropolitan areas, with a limited top speed of 150 km/h (93 mph) and without manual gearbox it is more important to respect the inner city speed limit rather than to compare at a glance speed and revs to choose the right gear. To partly compensate the higher mental workload of reading digital numbers instead of interpreting a pointer angle, the speedometer numbers are more than double the size recommended in EN ISO 15008:2009 and form the center of the instrument.

Below, a drive train gauge is the only remaining indicator resembling an analogue instrument. It shows current deployment or regeneration of electric power and provides subtle efficiency information: The blue brooch marks the limits of efficient acceleration and deceleration (without using the foot break the white pointer would not exceed the left efficiency limit). The thickened zone around the coasting point in 6 o'clock position recommends a smooth driving style which results in moderate needle movements (white marker). Few information on this instrument have its exclusive display areas, like current speed and range. Large parts of the display area are used in multiple ways: A Check Control Message or person warning overrule fill levels and trip, but never current speed and electric range (Fig. 3).

Fig. 3. Cluster Instrument BMW i3 (Fotocredit: BMW Group): Check Control Message (left) and person warning (right) overrule information of lower priority

Total mileage, clock, and current consumption is default content on most BMW cluster instruments. Here, a rigid selection had to be made: The clock is anyhow shown on most iDrive menus (in the status bar) so it was integrated into the on board computer list. There one can also toggle to total mileage and current consumption. This reduction of information density and unnecessary redundancy is what is meant by "clever simplicity". More than ten layout versions were designed and evaluated in expert assessments, in the end three were extensively tested in the mentioned usability tests on the driving simulator and on board the I/0ne test platform, leading to significant changes from each iteration step to another.

3.2 Gear Selector

As the drive train of the car is operating with a fixed gear, the user can only choose between P, R, N, and D. No manual gears have to be selected. This also means that the interaction frequency is lower in comparison to a car with manual and automatic gearbox. However, it quickly became clear that this component demanded for a specific set of requirements, including ergonomic, technical, and aesthetic aspects. Amongst these are

- Distinctive representation of the electric drive train
- Defensive interaction gesture in contrast to "sporty" gear shift sticks
- Clear semantic concerning mechanical degrees of freedom
- Optimized interaction without visual control
- Still full visibility and reachability for all percentiles

Moving the gear selector functions to the steering wheel area can be made in multiple ways. Push buttons for P, R, N, and D are one option, as realized in other EVs/cars on the market, but this form of interaction requires additional hand-eye-control and may increase driver distraction. Literally hundreds of sketches and long discussions later the following design took form: A rotary, monostable control, mounted on the steering wheel with the scheme aside (Fig. 4).

Fig. 4. Gear shifter BMW i3 (Fotocredit: BMW Group)

This design allows achieving another advantage: Compatibility between operation direction of the control and the activated direction of drive. So, moving the rotary lever forwards activates “D”, pulling it backwards “R”. With respect to the target group of novice users who typically perceive the classic automatic gearbox scheme P-R-N-D with “P” in front and “D” in reverse position as a hassle, this is a clear progress towards intuitiveness. Tests also confirmed that users who are accustomed to the classic scheme very quickly adopt to the inverted i3-logic – thanks to the combination of new position, new touch, and new interaction gesture.

At the same time the position behind the steering wheel and the kinematics that require the deployment of a momentum, make unwanted operations (by falling objects, playing children,…) practically impossible. As a consequence we also omitted the shift lock button which is integral part of all BMW gear shifters. The START STOP-button (SSB) is integrated as well, with slight restrictions in terms of reachability but optimal visibility. The close grouping of SSB and rotary control also makes it comfortable to drive off with one hand gesture – like the one-pedal-feeling does by reducing the number of shifts from one pedal to the other. The design also allows to integrate a READY indication which is important when it comes to mode awareness.

3.3 Indicating READY State

The silent start of an electric car is fascination and system ergonomic challenge at the same time – this is a clear feedback from the usability tests: Unambiguous feedback on whether the car is in ready state or not is crucial to avoid user irritations because of the missing engine sound. Note that the BMW i3 is equipped with keyless go and does not have a key insert. Finally, a combination of visual feedback in the cluster instrument, visual feedback on the gear shifter, and acoustic feedback is indicating READY. After unlocking the car and opening the door, a short welcome animation is shown. It remains in the state depicted in Fig. 5.

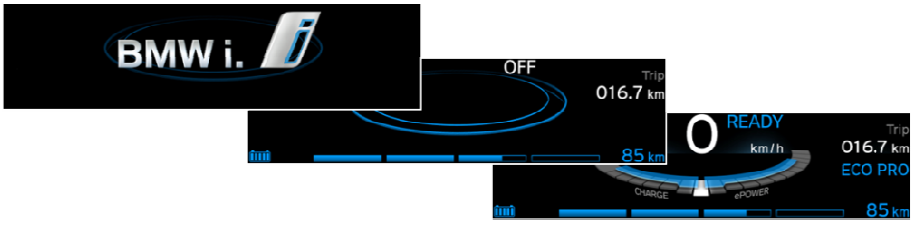

Fig. 5. Cluster Instrument BMW i3 (Fotocredit: BMW Group): Welcome (top), STAND BY (middle), READY (bottom)

In this state practically no primary, secondary of tertiary functions are available which is symbolized by an empty screen. Pushing SSB without footbrake leads to STAND BY state. Now all iDrive-functions are active, range and fill level are alive, on board computer can be toggled. But it takes pushing the footbreak to activate READY state. Now current speed is displayed, the drive train gauge is shown, and

READY is depicted explicitly. This differentiation helps to distinguish the states and still highlights the only state with full functionality.

Simultaneously, an orange light band embracing the SSB keeps flashing in all non-READY states to catch the user's attention and help him find the first step to get the car started (Fig. 6). As soon as the footbrake is pressed, the flashing becomes brighter. In the transition phase towards READY state, the light band first expands towards the rotary lever and then changes color to electric blue. This color coding was chosen to indicate electricity as well as efficiency messages. The expansion of the light band unites SSB, scheme, and rotary lever and so conveys the message: "time to turn the lever".

Fig. 6. Gear Shifter BMW i3 (Fotocredit: BMW Group): non-READY state (left), transition to READY state (middle) , READY state (right). Night design, "P" active.

Additionally, an acoustic sound indicates activation (increasing frequency) and de-activation (decreasing frequency) of READY state. In contrast to the indications in cluster instrument and gear shifter, this indication is temporary during the transition phases to preserve the quietness of the car but feedback when necessary. Of course it is fundamental that all three feedback mechanisms work together synchronously.

3.4 Selected e-Mobility Functions of iDrive

To enhance comfort or to convey efficiency information as requested during the field tests, several e-mobility specific functions were added, and some were removed: As range plays an important role the user wants to be in control how to use onboard electricity. Dominant factor is the driving style and a large set of functions help to drive efficiently (drive train gauge, ECO PRO modi), to motivate the user (ECO Tips, efficiency challenge via smart phone app,…), and to offer solutions before situations become critical (see section 3.6).

But an influencing factor is the usage of auxiliary consumers, too - especially A/C. The car heating in the winter can reduce the net range drastically. 2°C more or less cabin temperature can make the difference if the destination can be reached or not. In order to provide maximum transparency, a highly reliable range prediction is calculating in real time. Additionally, the new menu "Auxiliary consumers" clearly depicts how much range is currently consumed by the A/C system. This menu also indicates the effect of the seat heating which issurprisingly low: Setting both seat heatings on MAX would always result in a range reduction below 1km. With this information the user can easily decide how to compromise best between climate comfort and range (Fig. 7).

Fig. 7. NewiDriveMenue "eDRIVE" BMW i3 (Fotocredit: BMW Group): Auxiliary Consumers. Seat heatings are turnedoff, so no range potential is displayed.

On the other hand,functions from the BMW i3 predecessor BMW ActiveE were abandoned to reduce complexity, to avoid irritations amongst our non-early adopters clientele, and simply because improved technical solutions have been found which made monitoring of certain parameters unnecessary. The BMW ActiveE "eDRIVE" menue "Battery Info" is a good example for that (Fig 8). It gave technical insight into the state of health of the high voltage battery, including the parameters battery temperature and state of charge (SoC) in [%]. It has been removed from the BMW i3 menus, raising questions among the early adopters community. The reason is: In contrast to the MINI E and BMW ActiveE cars which the early adopters have been using for a long time, the BMW i3 is equipped with a highly effective thermal HV-battery management and, as already stated, a very reliable range prediction.

Fig. 8. Removed iDriveMenue "eDRIVE" BMW ActiveE (Fotocredit: BMW Group / A0145735.): Battery Info including Battery Temperature, SoC, and Range.

As both was not the case in MINI E and BMW ActiveE, users were accustomed to make their own range calculations and therefore needed SoC in [%]. Also, monitoring battery temperature used to be necessary to predict degradation effects – in the rare case of a degradation this information is now integrated in the BMW i3 drive train gauge.

3.5 Charging the Car

To increase intuitiveness, charging functions were redesigned from the socket to the app: The cable is stowed in its own compartment to keep the interior clean and tidy. The plug socket is brightly illuminated to facilitate connecting at night and also incorporates a clear color and frequency coded indication of all relevant states, e.g. "charging" with blue flashing and "fully charged" with constant green (Fig. 9).

Fig. 9. Charging features of BMW i3 (Fotocredit: BMW Group / A0145735.). Top: Cable box under the bonnet, illuminated socket, Goodbye Screen. Bottom: BMW iRemote App, charging screen (range extender version).

After plugging in, the instrument cluster converts into a charging screen, informing about all relevant details such as time until full charge or chosen timer settings and range after a full charge. To keep operation easy, by default the user does not have to make any difficult decisions or settings: Just plug in and charge. Those who use the car regularly will find the week calendar helpful. It allows to set departure times and precondition battery and cabin – a feature that enhances comfort and range. All these settings are kept very clean, and when the drive is ended with a push on the SSB, a "Goodbye Screen" is shown, summing up the most important parameters. Also, setting changes can be made right from that screen. Charging progress, timer settings etc. can always be monitored via BMW iRemote App to ensure flexibility and to keep the user informed about the vehicle status – push and pull wise.

3.6 Selected Satnav Functions

A powerful set of satnav functions will help to cure "range anxiety": By default the map provides two outlines indicating the range in all directions in current drive mode and in the most efficient one named ECO PRO + (Fig. 10).

Hereby, traffic conditions, topography, week day, temperature, and road net are incorporated, calculated on the backend server. Also charging stations can be displayed, including detailed information on socket types and (depending on data provider) availability and ChargeNow readiness. In Fig. 10, close to the current car position a green symbol is half hidden. It represents a user chosen "preferred charging station".

Fig.10.iDrive menu "NAV" BMW i3 (Fotocredit: BMW Group): Range map

Fig.11.iDrive Range Assistant BMW i3 (Fotocredit: BMW Group): Pop up

A so-called Range Assistant permanently monitors it and as long as the symbol is green it is possible to reach it. If returning there becomes tight, a pop up window warns in time, providing alternatives how to get back safely (Fig. 11). This happens independently of the navigation system guiding status. But the range assistant also takes action if range and distance to destination do not match, shown in Fig 11, too: The flag symbol represents the current navigation destination, the plug the favorite charging station. In the header in blue "Electric range not sufficient" is inscripted, providing the alternatives to change route criteria to ECO PRO Route, to select ECO PRO + mode or to search for charging stations along the route. In this example, only switching to ECO PRO + mode would allow to reach the destination *and* get back "home". Again, the layout of the pop up window was iteratively modified until it got its dominantly graphical expression: It allows a quick comparison between the criteria "arrival time", "buffer", and "comfort" (note that ECO PRO + switches A/C off – the user is informed about that when ECO PRO + is activated) – which the user prioritizes situatively.

4 Conclusions

Selected aspects of the BMW i3 UI show how MINI E and BMW ActiveE field tests laid the road to its development. The user's voice has been constantly heard over a

period of 6 years, additionally including numerous iteratively applied testing methods corresponding with the increasing level of BMW i3 UI maturity (cf. also [4]). A particular challenge was the application of a highly minimalistic yet clever approach which underlines the whole “project i”story. We are convinced to deliver not only ease of use but also: Sheerpleasure.

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