User-centered Development of a Visual Exploration System for In-Car Communication

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Abstract. Modern premium automobiles are equipped with an increasing number of Electronic Control Units (ECUs). These ECUs are interconnected and form a complex network to provide a wide range of advanced vehicle functionality. Analyzing the flow of messages in this network and tracking down problems has become a major challenge for automotive engineers. By observing their working practices, we found that the tools they currently use are mostly text-based and largely fail to provide correlations among the enormous amount of data. We established requirements for a more appropriate (visual) tool set. We followed a user-centered approach to design several visualizations for in-car communication processes, each with a clear purpose and application scenario. Then we used low-fidelity prototypes to evaluate our ideas and to identify the "working" designs. Based on this selection, we finally implemented a prototype and conducted an expert evaluation which revealed the emergence of a novel mental model for thinking about and discussing in-car communication processes.

Key words: Information Visualization, User-centered design, In-Car Communication Networks

1 Introduction

An increasing variety of functionality is provided in premium automobiles to enable more efficient, enjoyable, and safer driving. This has led to an increasing amount of hardware in the form of Electronic Control Units (ECUs), as well as new software components in these ECUs. In the last several years, many innovations and new functions were realized by interconnecting ECUs to share information within the vehicle in new ways. The tremendously increased complexity of today's in-car communication networks is the consequence. Modern premium automobiles currently contain up to 70 ECUs, interconnected by four major bus technologies (CAN, MOST, FlexRay, LIN). Some of these ECUs are even connected to all of these bus technologies, and a massive amount of information is distributed by exchanging messages. Current in-car communication networks have to deal with up to one million messages per minute, and each message in turn transports a certain amount of signals representing sensor measurements and status information.

With this increasing complexity, engineers are more and more challenged in terms of analyzing errors and diagnosing faulty vehicle behavior. They are persistently confronted with an enormous amount of data generated by bus traffic scans and network simulation systems. To address this problem, specific tools were developed to support analysis experts in comprehending in-car communication processes. However, the tools that are currently available are mainly based on textual descriptions and lack presentation of cause and effect relations. However, to gain a deeper understanding of the bus communication, it is necessary to clearly see the temporal (or even causal) relation between messages.

To support this communication analysis, we propose a graphical representation of the temporal relation between messages. We describe our three-phase, user-centered design process and the experience with applying our tool in a real, industrial environment for the diagnosis of in-car communication. The fact that this is a true expert domain requires close cooperation with users to clearly understand their working practices and to fine-tune solutions to their needs. Tools which do not adhere to this design strategy will most probably turn out to be inappropriate [17]. In this paper we present a working example how a user-centered approach can be applied to design information visualization in an industrial environment, namely the automotive industry, and how this led to an novel, appropriate visualization concept. A central point of our approach is to involve domain experts - the rarely available automotive analysis experts - closely in every stage of the design process. According to the specific requirements of each phase we used different human-computer interaction (HCI) methods to obtain a suitable, comprehensive visualization design. We used user observations and guided interviews in the analysis phase, evaluated a number of designs by means of low-fidelity prototypes and conducted an expert user study with a fully implemented prototype in the evaluation phase.

2 Related Work

In HCI, many people have investigated user-centered design approaches [8, 11, 12]. However, in the field of information visualization designers often neglect these HCI principles and develop inappropriate system designs. In the recent past, things have started to change and the fundamental relevance of a user-centered approach for the success of information visualization systems is recognized in [3, 6, 14, 17, 19]. Wijk [17] for instance ascribes the fact of many poor designs to a gap between the visualization researcher and the domain experts. The design often suffers from the fact that these two parties have an entirely different background and expertise. Wijk therefore proposes a user-centered design approach to clearly understand the end users' needs and limitations. Wassnik et al. [19] also discuss the adaption of user-centered design approaches from HCI and their transfer to interactive visualization systems. They propose a highly iterative design process with prototypes of different fidelities and their evaluation. Particularly, a detailed analysis of the users, their tasks and environments is strongly recommended to solicit actual needs. A few existing projects have already applied a user-centered approach to develop information visualization systems. Goodall, et al. [4] for instance designed a visualization system to support network traffic analysis for intrusion detection. To get insight into the users' needs they used contextual interviews [7] and derived system requirements for this specific application area.

In the analysis of current working practices, we found several expert tools used by automotive engineers to analyze in-car communication data. These tools are directly related to our work because they represent the current practices, which we want to improve by extended use of information visualization concepts. Canalyzer[1] is one of the most frequently used software tools. It is an expert analysis tool integrated into a tool chain to work with automotive bus systems and communication networks and the de-facto standard tool for error diagnostics and network analysis. The user interface of Canalyzer has shaped the way in which engineers think and work right now. It provides a variety of modules to textually represent data in lists and also supports some basic, non-interactive visualization, such as line and bar charts, gauges, status bars, or a topology view of the ECU network. While on the technical realization side, this tool provides a wide functionality and professional way to support the engineers' needs, there is a high potential for improvement by providing interactive information visualization. Several other tools are available and used for analyzing in-car communication processes. One relatively new tool is Tracerunner[2], which differs from the rest by a stronger use of color coding and the occasional use of relatively sophisticated visualization techniques. In addition to the textual information, for instance a map can represent GPS data, a compass can show the current orientation or a speedometer can be displayed. Furthermore, there are several in-house tools from automotive companies which have roughly the same use case mapping and functionality range as Canalyzer or Tracerunner. These tools are mostly directly adapted to product-specific requirements. One common observation was that none of these tools really supports the user with interactive information visualization techniques.

3 Analysis: Current Working Practices and Users' Needs

Studying the User: In order to design a system for such a special target group, it is very important to clearly understand their current practices and needs [19]. We conducted two different kinds of user studies for this. First, we used a mixture of a user observation and a guided interview to get direct insight into the daily routines of the experts. Two observers sat next to one analysis expert, observing his/her daily work, taking notes and asking questions about unclear points. Then, we enriched these observational studies with guided expert interviews to directly focus on our interests - the current use of visualization

[1] `http://www.canalyzer.de`
[2] `http://www.tracerunner.de`

and the expected added value of visualization in this area. The interviews were conducted after the user observations. In doing so, we avoided distorting the results of the observational studies by prematurely informing the user about our interests. We conducted these studies with eight experts, all working in the analysis and diagnosis of in-car communication processes. Each study took 1-2 hours depending on the amount of time the experts were willing to contribute. In a second step, we designed an online questionnaire to contact a wider range of analysis experts and to directly address our findings from the observations and interviews. The focus was mainly on currently used tools for diagnosis, the variety of use cases they have to deal with, and the current usage of visualization. In this process, we received feedback from 23 more experts and confirmed our previous findings.

Results of the Studies: Not surprisingly, we encountered a very *high degree of specialization* in the underlying domain. When watching an engineer browse through an in-car communication network data trace, a layman would not be able to follow the quick and complex thoughts and conclusions which are made within seconds, mostly because of the complex and very specific way in which engineers read and interpret the data shown in hexadecimal code. Every engineer has her/his expertise in one particular field of the network, for instance in two motor management ECUs. All codes used there are familiar to the engineer and easy to interpret. But if the expert wants to explore data beyond the usual, well-known scope, s/he has to browse through unknown, non-interpreted hexadecimal code and mapping the functions soon becomes a tenacious and time-intense activity. The most important software tools were Canalyzer and a number of in-house tools. Which tools the engineers preferred, mostly depended on personal preferences, usage by colleagues within the same department, capabilities of the tool and license fees. The tools are mostly based on textual description of communication data with long lists of raw communication data. This *raw data is very important* for the engineers to exactly understand the details in the communication process and to identify the precise point of failure. However, for understanding coherences, dependencies, and trends this form of data presentation is useless. The tools also support some basic visual descriptions, for instance a line graph or progress bars for signal values. However, in the interviews and questionnaire we learnt that these visualizations did not match the experts' needs. All subjects strongly demanded a higher degree of visual support in the analysis process. Furthermore, we found that users frequently worked with *multiple parallel and sequential views* to provide different perspectives of the same dataset (e.g., a line chart and a hexadecimal information list), for simultaneously looking at different timestamps (e.g., looking for similar or cyclic settings), or for comparing different datasets. Although these multiple views were often used, the current tools poorly support a proper coordination between them.

Derived Requirements: From our formative studies we derived the following common requirements for improving the current practice:

Enhance Visual Support and Interaction: Novel visualization methods have to be considered and evaluated regarding their usefulness and adequacy for human perception. While the detailed representation in current tools is sufficient for parts of the task, visualization techniques must be used to gain more insight into correlations, dependencies and overview aspects. Additionally, the subjects of the studies demanded those visualizations to be highly interactive and to support direct manipulation [13] to allow usable and extensive exploration techniques.

Support Preattentive Processing: Human perception is neither efficiently used by browsing endless data tables nor by recognizing small hexadecimal changes within them. However, the users we observed spent plenty of time searching and navigating these lists. The effect of preattentive processing [15] of certain graphical features, such as color or shape, can reduce the perception time for the existence, absence or number of graphical items on the stage. Including this consideration into the design process means keeping the colors and shapes of any visual vocabulary as simple and subtle as possible, whereas any important point of interest should pop out of the surroundings [18, 16].

Quick Access to Raw Information: Any piece of raw data from signals, messages and values must be reachable at any time. An abstraction of the data can be helpful, but is not preferred for showing hard facts. Hence, the classical List View with its rich level of detail will remain a central point in the user interface.

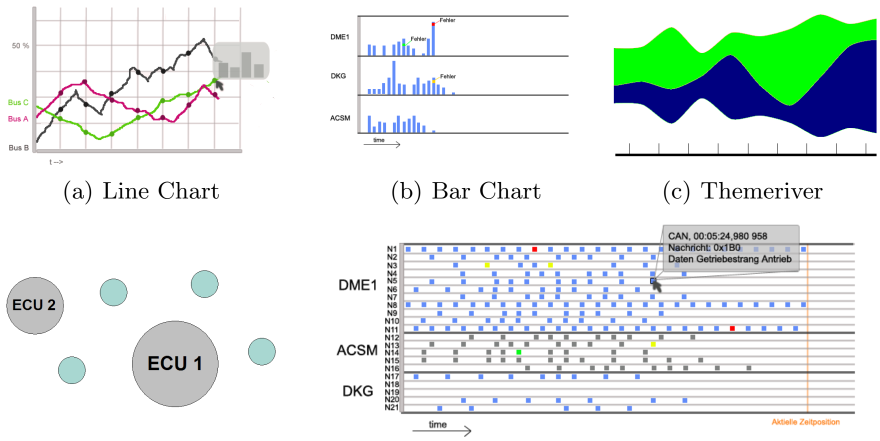
Enhance Temporal Structure and Navigation: In-car communication traces have a strong inherent temporal structure. Message after message is recorded and written into the trace file sorted by time stamp. However, navigation and orientation in time is poorly supported by the current analysis tools. They just put all the information in scrollable, ordered lists. As the lists get very large, this requires a lot of scrolling effort, and - even worse - reduces data to its causal order and actually hides exact time differences (which can only be found by looking into the detailed information). However, to better understand all temporal relations, both coarse and fine time information is relevant.

Multiple Coordinated Views: Observing the connection between different visual data representations can increase the understanding of complex relations in the datasets. We therefore propose the explicit support of multiple coordinated views (MCV, [9]). While current tools make extensive use of multiple views, these are poorly coordinated. A clear and usable coordination concept should support the user in browsing the data and allow easy switching between views.

4 Design: Creating and Evaluating Novel Approaches

Generation of Ideas: In the idea generation phase, a visualization catalog was collected, which contained existing views, newly developed visualization concepts and adaptations of traditional solutions. The proposed concepts were:

- *Textual List View:* The traditional List or Table View is the most familiar way to show detailed data and it is extensively used in current tools.
- *Classic Visualization Methods*: Line and bar charts are frequently used visualization methods. They are easy to understand and therefore have a huge



(a) Line Chart (b) Bar Chart (c) Themeriver

(d) Bubble View (e) Autobahn View

Fig. 1. Visualization catalog

potential for representing time-dependent data sets. They have represented the way people use and think about information visualization for the past couple of decades (cf. fig. 1 (a) and (b)).

– *Themeriver:* The Themeriver [5] visualization uses a “river” metaphor with different “currents” varying in width to represent data values. The purpose of the Themeriver is to give a general overview of trends within time periods of datasets. (cf. fig. 1 (c)).
– *Bubble View:* The Bubble View was based on scale-free networks [1] used in bioinformatics. It visualizes different points within an in-car network, for instance ECUs or functions implemented in the ECUs drawn as bubbles and directed graphs with arrows between them. Whenever the activity of such a component increases, the corresponding bubble starts to grow. This was meant to present a current state of the system and show the “big players” at a certain time. (cf. fig 1 (d)).
– *Autobahn View:* The Autobahn View is a novel visualization concept which we designed according to the outcomes of our analysis phase (cf. section 3). The Autobahn View is based on the metaphor of a crowded highway and on the fundamentals of a scatter plot. Each bus system is visualized as a separate group of lanes - the highway. Every bus transports messages from different ECUs represented by an incorporated horizontal bar - a lane of the highway. The lanes in turn contain black rectangles - the cars - which each represent a message sent by the ECU through the bus to another ECU, ordered horizontally by time. A slightly different view was defined as the Signal-Autobahn View. This view inherits all principles of the Autobahn View, but represents transported signals instead of messages (cf. fig. 1 (e)).

Table 1. Results of visualization catalog evaluation

View	Figure	Desire	Reasons	Mapped use cases
Textual List View	-/-	Strongly requested	The list view is irreplaceable to show the detailed data in tabulated format (cf. Current Working Practices)	- Showing precise detailed information - Exploring data - Monitoring data - Analyze data
Classic Visualization Methods	1 (a) 1 (b)	Optionally requested	These visualization forms are well known and easy to understand. Experts like using them but demand a higher degree of interactivity.	- Showing state of the components - Showing activity history of components - Showing traffic volume - Finding transition states
Themeriver	1 (c)	Not requested	High abstraction level with less level of detail was assessed to be not applicable to the in-car communication domain.	- Showing combined trends
Bubble View	1 (d)	Optionally requested	Although this view had no direct use case mapping it was extremely well liked in discussions because of its innovative character.	*No use cases found*
Autobahn View	1 (e)	Strongly requested	This visualization reached a wide acceptance by the expert users because it supported a common mental model with a simple and pleasant visual vocabulary.	- Finding Errors - Monitoring Cyclic Traffic - Monitoring the In-Car Communication - Getting familiar with the car network domain - Explore Cause-Effect relations

Low-Fidelity Prototypes and Evaluation: To evaluate our design ideas, we discussed printed versions (cf. fig. 1 (a)-(e)) with the same 8 experts we had observed in the analysis phase. Their input narrowed the visualization concepts down very quickly and led to a short list of pragmatic design solutions. We asked them to assign use cases to the visualization concepts and to imagine and illustrate in each case an example how it can be used to visualize the underlying data, e.g.,: "In my opinion the Autobahn View could be used to show message bursts and to investigate frequencies in sending actions". Based on this evaluation, we classified the visualization concepts into three categories: Strongly requested, optional, or not requested. The results of this classification as well as the reasons and the mapped use cases can be found in table 1.

5 Evaluation: Building and Evaluating a Prototype

Final Concept: In order to turn the basic concepts into a well-designed tool, we took the most requested visualization concepts, namely the Autobahn View and the List View, applied established design guidelines, worked out an appropriate interaction concept and integrated several features to support the users' working practices. These two visualization concepts form the basis of an MCV application, allowing the user to work with an arbitrary number of Autobahn Views and List Views, which can be interactively created. The two concepts each emphasize different kinds of information. The Autobahn View is used to visualize messages or signals, both based on their ECU affiliation. A List View can display detailed information about messages, for instance exact time stamps, included signals, long name, etc., or, alternatively, about signals, such as the signal's raw data. All input from the experts was used to design a coherent interaction concept

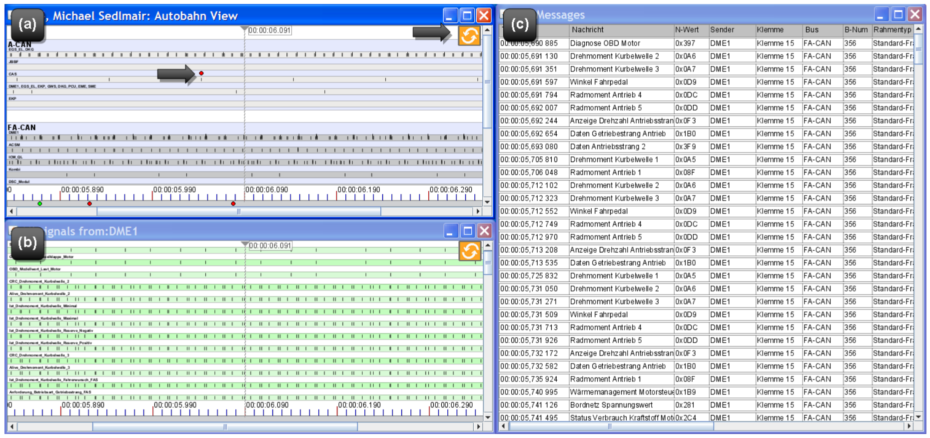


Fig. 2. Screenshot of the application with (a) Message-Autobahn, (b) Signal-Autobahn and (c) Message-List / Additional arrows show a POI (left) and Sync Button (right)

within the views and a coordination concept between the views. Figure 2 shows a screenshot of the implemented system.

As an implication of our design requirements, the final concept adheres to Shneiderman's visualization mantra *Overview first, zoom and filter, details on demand* [13]. The Message-Autobahn View forms the central part and window of our application. It is the only view restricted to a single instance and makes all messages of a given data trace accessible. In general, the Autobahn View is based on the zoomable interface paradigm (ZUIs, [2]). Two-dimensional panning is accomplished by grabbing the view, and zooming by the mouse's scroll wheel. Navigating along the x-axis, therefore, enables the user to go back and forth in time in a convenient and familiar way. At the lowest zoom level, the Autobahn View accommodates a coarse-grained representation, showing many messages without fine-grained timing information (*Overview*). The entire representation is arranged on a horizontal timeline and can show up to 5000 message items in a time frame of up to 3 seconds on one screen.

By an animated zoom, which takes not more than 300 msecs, the user can easily get to a higher level of detail (*Zoom*). Fig. 3 shows a sequence of interactions to zoom in to a specific area within the trace. Finding the right levels of time granularity for each of the four zoom levels was challenging. The car-system stores time stamps in microseconds. As our observation and interviews showed, engineers work mostly with milliseconds. The problem, that messages from the same millisecond, but different microseconds would be shown as parallel, was discarded by engineers non-critical. Nevertheless a compromise was implemented in the form of a user-selected switch between steps of 100 micro- and 1 milliseconds. In addition, to emphasize the aspect of overlapping messages in the milliseconds view, a subtle number was set up next to the highest item which contains the number of messages within this cluster of parallel messages.

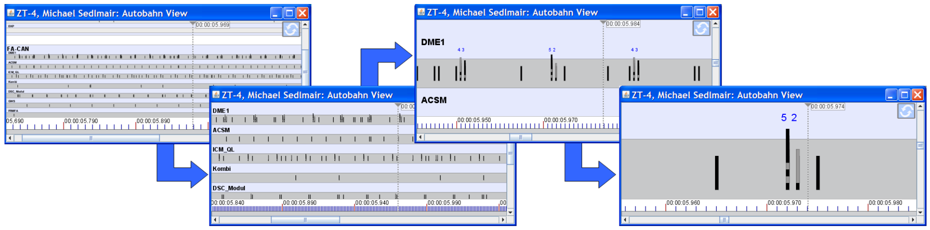


Fig. 3. Zooming stepwise into the Autobahn View

Since not every message or ECU is necessary for a particular use case, a filter functionality lets the user switch ECUs, messages, signals, or even entire bus systems off or on (*Filter*). As all the users had a technical background, a Boolean syntax was used in a textual filter dialog, e.g., "NOT message-name1 AND NOT message-name2".

To support the required quick access to non-abstract data, our application provides three ways to reach this kind of raw data (*Details on Demand*):

– *Selection:* Every message or signal on the Autobahn View is clickable. This single selection opens the List View with all available detail of that particular message or signal. Besides the single selection, the user can select multiple items by pressing CTRL and drawing a rectangle over the area for which more information is desired.
– *Preview:* Every message or signal item on the stage provides a mouseover preview showing the name, the hexadecimal code and the time of this message.
– *Context Menu:* In order to show all listed details from one ECU or message, the user can issue commands such as "List all details" via a rightclick menu.

To support orientation within the mass of time-based data, we integrated a marking concept to *support preattentive popout effects*. We used visual markers in the form of circles filled with exaggerated, saturated colors to emphasize certain messages or signals - points of interest (POIs) - within the Autobahn View. The circles are positioned directly over the associated item in the view and pop out from the pale background. For differently colored POIs inter-POI preattentive distinction is not supported. In addition, they are shown in a so-called overview bar. This allows direct navigation between POIs along the entire timeline (cf. fig. 2). The concept of POI highlighting is used for:

– *Anchors:* These are user-defined marks, which can be interactively added to the stage and filled with explanatory text.
– *Search:* Search queries can be created through a separate component in which the user selects certain messages or signals and the system highlights all matching items. Query parameters are the highlighted color, the name of the message or signal and an optional value range for signals. A typical search query would look like "Signal xy>10".

Time synchronization between Autobahn Views is achieved by a variant of synchronous scrolling [9]. Every Autobahn View has a timedrop component, on which the local time of the view is shown by a text field and a dotted line. Next to the local time we show the global time which is used to synchronize the views. In order to synchronize a view to the global time the user has to push the synchronize icon placed in the upper right corner (cf. fig. 2). In doing so, the user adds this particular view to the list of already synchronized views. Browsing through the data in one of these views then triggers a time update and navigational action in all other views.

Implementation of a High Fidelity Prototype: Our prototype is implemented with java and uses the piccolo[3] framework for zoomable interfaces. The prototype is connected to real data sets recorded from in-car communication networks and can handle datasets of up to 200 000 messages. In the longer run, a more complex and portable system environment has to be implemented, which, however, was clearly not the focus of our research.

Evaluation of the Prototype: We conducted a qualitative expert user study to assess the understandability and the usability of our visualization. The subjects were five experts with long experience in automotive diagnostics and analysis and each study took 1-2 hours. The study was divided into three parts. First, we gave a short introduction to our tool with a concept video and a five minute testing phase. Then, the subjects had to solve several tasks to evaluate the tool's usability and to get familiar with the tool's paradigms. The tasks ranged from very elementary, tool-based to more sophisticated, domain-based ones, e.g.,: “Open a new view and synchronize the views”, “Find a specific message”, or “Find abnormalities in the communication of the ECU LRR”. In this phase we used the think aloud protocol to capture the subjects' opinions, criticisms and ideas. Finally, a guided interview was used for general feedback and to evaluate the understanding and insight provided by our novel visualization.

The overall feedback from the domain experts was very positive. During the studies we observed, that the Autobahn View provided a novel mental model for thinking and discussing in-car communication data. It is hard to measure this kind of insight [10] but it was very interesting to see four of five domain experts starting to explain things directly by means of the novel Autobahn metaphor, e.g.,: “As you can see, we have lots of traffic on this ECU's lane”, “Oh, what does that burst of message rectangles mean?” or “On the road you can perfectly track cyclic messages”. Another hint in this direction was an observation we made during a presentation with a live demo of our concept in a meeting of analysis experts. During the live demo, the attendees suddenly started to discuss a known problem of a specific ECU by means of the Autobahn representation. The problem was about the ECUs “spamming” activities on the bus and the engineers started arguing: “Does anyone know why the LRR ECU sends message bursts in this compressed cycle?”, “In my opinion that has to be the reason for the bus spam.”, “No, the other ECUs seem to work normally”, etc. The most appropriate use cases for our concept were the direct perception of message

[3] `http://www.cs.umd.edu/hcil/jazz/`

bursts and activity centers as well as the detection of frequencies and cycles within the communication data. Also, the fast availability of detailed information was very helpful for a more detailed exploration in these situations. The feedback on usability was also very positive. All subjects were able to use the interface fast and without major problems.

The final evaluation also showed problems and revealed room for improvement of our visualization concept. Most importantly, the stacking of nearly simultaneous messages was initially misunderstood by three of five of our subjects. It was interpreted as a length coding of information and guessed to be the messages' byte length. Enquiring this in detail, however, showed that coding the messages' length would not be beneficial for the engineers at all. After resolving the misconception, they had no further problems in understanding. Nevertheless, the initial misunderstanding must be taken seriously and considered in future work. Additionally, we detected an incompatibility in understanding the panning and zooming interaction concept with two of our subjects. They noted that they would prefer zooming via drawing a rectangle, which conflicted with our interaction concept for selecting a group of items. After several minutes of using the interface, this usability problem seemed to have disappeared and the subjects used the tool fluently. While this could be investigated further to avoid potential conflicts with established ways of interaction, it can also be argued that our target group consists of expert users, and hence an initial problem might be less severe than for one time users. Another point of criticism was the understanding of the coordination feature. Two of our subjects wondered that they had to select more than one view to start the synchronization action. Their current mental model matched more an "all-or-none" synchronization feature and the synchronization of sub-groups of views was not self-explanatory. In future work it has to be clarified whether the more powerful and dynamic group synchronization is worth the additional learning effort or whether a global synchronization for all views would perform better.

6 Conclusion and Future Work

We have presented a user-centered approach to designing a new, visually and cognitively well-founded tool set for automotive engineers to deal with complex in-car communication processes. Based on a detailed observation of our target group, we established a number of requirements for the design of this tool set. In the following design phase, we developed different visualizations, each with a clear application scenario in mind, and evaluated these designs with our target group. Based on these findings we implemented a prototype and conducted an expert user study which revealed the emergence of a novel mental model, called Autobahn View. After further iterative refinement (cf. section 5 - Evaluation) and enhancement of scalability (cf. section 5 - Implementation), we are planning to integrate our designs tightly with the existing tools and provide a stable working environment for day-to-day use.

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