Interactive Visual Analysis of Multiple Simulation Runs Using the Simulation Model View: Understanding and Tuning of an Electronic Unit Injector

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Abstract—Multiple simulation runs using the same simulation model with different values of control parameters usually generate large data sets that capture the variational aspects of the behavior of the modeled and simulated phenomenon. We have identified a conceptual and visual gap between the simulation model behavior and the data set that makes data analysis more difficult than necessary. We propose a simulation model view that helps to bridge that gap by visually combining the simulation model description and the generated data. The simulation model view provides a visual outline of the simulation process and the corresponding simulation model. The view is integrated in a Coordinated Multiple Views (CMV) system. We use three levels of details to efficiently use the display area provided by the simulation model view. We collaborated with a domain expert and used the simulation model view on a problem in the automotive application domain, i.e., meeting the emission requirements for Diesel engines. One of the key components is a fuel injector unit so our goal was to understand and tune an electronic unit injector (EUI). We were mainly interested in understanding the model and how to tune it for three different operation modes: low emission, low consumption, and high power. Very positive feedback from the domain expert shows that the use of the simulation model view and the corresponding analysis procedures within a CMV system amount to an effective technique for interactive visual analysis of multiple simulation runs. We also developed new analysis procedures based on these results.

Index Terms—Visualization in physical sciences and engineering, time series data, coordinated multiple views.

1 Introduction

The importance of computational simulation and simulation models in engineering cannot be overemphasized. The design and development of new products mostly follows the standard simulation workflow. First a model is developed for the phenomenon under consideration and then that model is used as a basis for simulation [3].

The common characteristics shared by most of the models, simple or complex, is that they are created from basic building blocks with well defined behaviors specified by a set of control parameters. The state parameters in such a model show how a block behaves given the values of the control parameters. A simulation usually determines the values of the state parameters at different instances of time. The values of the state parameters are exchanged among the blocks in the simulation model.

The connections and dependencies among the blocks and the overall structure of the model determine the model's behavior. A visual representation of the model, usually in the form of a 2D graph, captures these dependencies and allows an engineer to have good understanding of the model.

A simulation produces a set of values for the state parameters (simulation results) that captures the behavior of the model (given the values of the control parameters). However, this connection between the model (and its visual representation) on one side and the numerical data (as produced by the simulation) on the other side is often missing from the analysis. The engineer can use various visualization techniques and data views to get an insight into the simulation results and relate those results to the underlying model. However, there is still a gap, both cognitive and visual, that needs to be closed (in the context of interactive visual analysis). To mitigate this problem, it is possible to integrate the simulation results (a single simulation run) within the display of the simulation model (e.g., as done in Simulink [12]) or by "anchoring" the information display on the system model [14].

When dealing with multiple simulation runs, the same model is used with varying values of the control parameters. Closing the gap in such a scenario presents an even greater visualization challenge and no solution has yet been proposed. There can be thousands or tens of thousands of runs that can generate a huge amount of complex data. We need a visualization and analysis solution than can cope with this challenge and bridge the gap between the model and the simulation results.

In this application paper, we propose a new view, the simulation model view, that provides an additional context for the simulation results to close the gap between the model and data for multiple simulation runs. The view provides a 2D graph where each node represents a building block of the simulation model. Each block has the control parameters that are used to tune the simulation and the state parameters that are determined through the simulation run. The values of both the control and state parameters are displayed directly within the node in the simulation model view.

If there are multiple simulation runs, the simulation model view blocks should show multiple values of the parameters. Moreover, the descriptive parameters are often time-dependent making the problem even more complex. The simulation model view is integrated in a coordinated multiple views (CMV) system. The benefits of multiple linked views and composite brushing facilitate the use of the simulation model view, especially when dealing with multiple simulation runs.

We have evaluated our approach in the context of an application from the automotive industry. Diesel engine powered heavy-duty trucks need to meet lower exhaust emission levels to comply with

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emission regulations [4]. In addition, there are demands to increase the engine torque, the rated power output, and to reduce the engine fuel consumption. One of the key engine components that determines the emission levels and the engine performances is the Fuel Injection Equipment, more specifically the Electronic Unit Injector (EUI). Figure 1 shows a schematic of an advanced two-actuator EUI.

We modeled, simulated, and analyzed the Delphi E3 EUI [6]. The Delphi E3 EUI (Figure 2, left) has two independent, fast response precision actuators that can change the injection pressure level and adjust fuel delivery timing and duration. This approach provides the unique ability to achieve full pressure control at low and high engine speeds.

The main goal of the evaluation was to understand the injector and to tune it for three different operation modes: low emission, low consumption, and high power. Several domain experts (one of them is a coauthor of this paper) used the proposed approach to analyze the effectiveness of the approach. The simulation model view, as a part of a CMV system, received a very positive feedback, and domain experts were able to do the analysis much more efficiently.

The remainder of the paper is organized as follows. Section 2 provides an overview of the related work. Section 3 describes the application domain. The new simulation model view is described and discussed in Section 4. Section 5 provides an illustration of the visual analysis using the simulation model view. Section 6 concludes the paper.

2 Related Work

Visualization of large, high-dimensional, and time-dependent data sets is an important, large, and very active area of research [20]. Large data sets need to be presented in a visual form and analysts need to interact with the data [10]. Data visualization techniques should be well suited for the given data set, have limited visual overlap, be easy to learn, and recall. One goal is to reduce the cognitive load when performing analysis tasks while providing good integration with traditional techniques (including simulation) to improve the data exploration process.

A combination of different views, combined with advanced interactive brushing, supports iterative visual analysis by providing means to create complex, composite brushes [5]. Those brushes span multiple views and they are constructed using different combination schemes.

The information mural view [9] provides a miniature version of the information space using visual attributes (gray-scale shading, intensity, color, and pixel size) and antialiased compression techniques. The view alleviates problems due to the limited number of pixels on the screen and the resulting information bandwidth constraints.

The table lens view [16, 17] uses a focus+context (fisheye) technique for tabular information and displays important label information and multiple distal focal areas. The view is used for visualizing and making sense of large tables using a graphical mapping scheme for displaying table contents by fusing symbolic and graphical representations into a single, user customizable coherent view. The user can control the number of colors used and the color mapping.

2.1 Time-Dependent Data

Time-dependent data is a very important category of data sets. Brushing the time axis to display details of the selected time frame is one very common and useful interaction technique used with static representations. Müller and Schumann provide an overview (taxonomy) of the visualization methods for time-dependent data [15] and discuss general aspects of time-dependent data. The time factor requires a special treatment during visual exploration. They distinguish between two cases based on the time dependency of the visual representations, time-dependent (dynamic) and time-independent (static) representation. In addition, they discuss data versus event visualization and conventional versus multivariate display. Multivariate data visualization techniques include the *ThemeRiver*, *Spiral Graph* and several special visual metaphors such as *Calendar View*, *SpiraClock*, *Lexis Pencils* and others.

The *ThemeRiver* visualization [8] shows thematic changes in a large collection of documents in the context of a time line. The collection (time line, selected content, and thematic strength) is shown as a river (flow, composition, and changing width). Colored currents in the river represent individual themes.

Aigner et al. [1] provide an overview of visual methods for analyzing time-oriented data and discuss general aspects of time-dependent data.

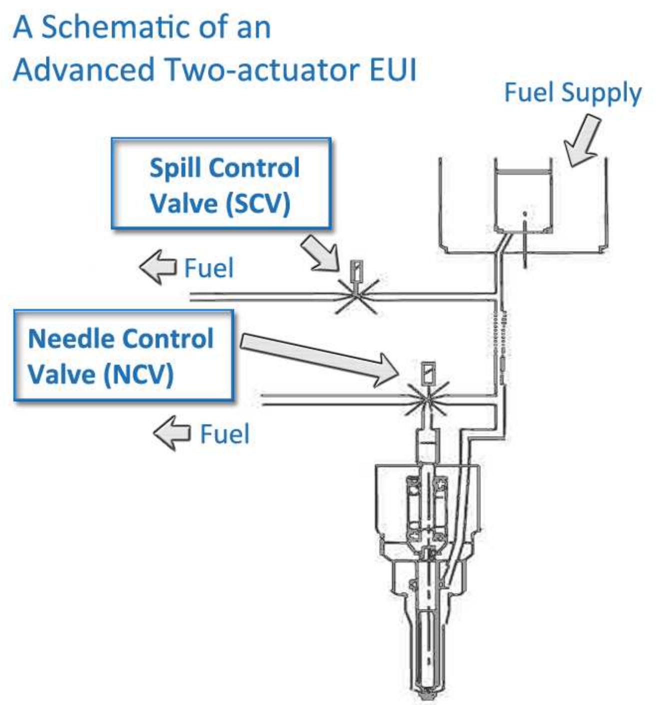

Fig. 1. Controlling fuel injection with an EUI. SCV controls pressure gradient and level. NCV controls needle opening and closing. Both of them are electronically controlled.

2.2 Application Domain

An advanced electronic unit injector with two electronically controlled valves can provide a very flexible choice of fuel injection characteristics. Single-cylinder engine tests have demonstrated the potential of such EUI systems for a heavy-duty diesel engine [6].

The optimization of the Fuel Injection Equipment system is very important in order to understand the evolution of pressure during the injection event, the multiple injection interactions with injector and

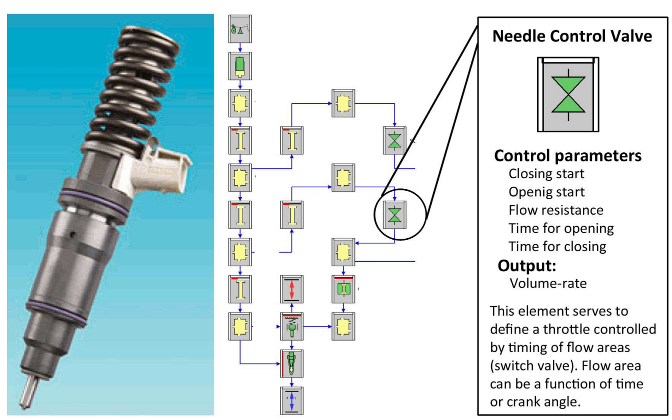

Fig. 2. The Delphi E3 Diesel EUI (left), the corresponding model view (middle), and a description of one of the NCV blocks from the model (right).

cam features [4]. The modeling of the simulation of the Delphi E3 EUI shows how the full integration of the modeling work in the design process contributes to the understanding and the optimization of injection system features and its engine environment design.

3 The Electronic Unit Injector

Strict emission regulations and the need to make engines as efficient as possible represent two main constraints in automotive engine design today. Engineers work hard on improving existing engines in order to meet these constraints. An optimally tuned injection system is one of the key components of an efficient modern engine.

There are several different types of injection systems in cars and vehicles. Currently, the two most important ones for Diesel engines are common rail and unit injector systems. The common rail systems have a fuel pressurized to the injection pressure in a fuel rail which feeds the cylinder. The rail is common to all cylinders.

The unit injector systems have the high pressure fuel pump integrated with the injector. There is one injector/pump per cylinder that is installed into the engine cylinder-head assembly.

The predecessor of the modern unit injector system was the patent from 1911 which shows the working principle of the unit injector. It took a long period of time until the technology was advanced enough to enable reliable and cheap production of unit injectors. The production started with unit injectors for large locomotive engines and heavy duty engines. In 1998 unit injectors started appearing in passenger cars.

In this work, we analyzed the Delphi E3 Diesel EUI [4, 6]. This is an advanced Diesel fuel injection system with two independent, fast-response precision actuators that can change the injection pressure level and adjust the fuel delivery timing and duration. This technology gives the unique ability to achieve full pressure control at low and high engine speeds.

The main parts of an EUI are: the nozzle, the needle with its return spring, the needle control valve (NCV), the spill control valve (SCV), the plunger, the plunger spring, and the electrical connector.

We first briefly describe the basic functionality of the unit injector. Figure 1 shows a basic schematic of the injector. The fuel comes into the pressure chamber. At the beginning of the pumping (used to increase the pressure) fuel escapes through the normally open SCV. The fuel can freely flow to the fuel gallery which is connected to the fuel tank.

When the electronically controlled SCV closes, the fuel pressure builds up in the system (and when it opens the fuel spills and the pressure drops).

The electronically controlled NCV controls whether the pumped fuel pressure is applied to the nozzle needle. The needle has a spring which pushes it down, and the fuel pressure can be used to support the spring and to apply much higher force to the needle (in the closing direction). The NCV allows the timing of the opening and the timing of the closing of the nozzle needle to be determined electronically.

If the NCV is activated throughout a period when the SCV is closed then the nozzle opens and closes according to the nozzle opening pressure and the nozzle closing pressure, set by the nozzle needle return spring only. This mode of operation and injection characteristic is the same as that produced by the single-actuator EUI system.

If the SCV is closed before the NCV is activated, then the fuel pressure can be pumped up to a much higher level before the NCV is then activated to allow the nozzle needle to open. Because the pressure applied to the needle (in the closing direction) is controlled by the SCV, a much higher pressure is needed to open the needle. If, towards the end of injection, the NCV is deactivated before the SCV is opened, the needle can be closed very fast with a high needle closing pressure.

The two EUI valves have the capability to precisely control multiple injection events. Accordingly, the needle opening pressure, the injected quantity, the hydraulic separation, and the needle closing pressure are dependent on the way the SCV and the NCV are activated. All of those events can be controlled for a pilot, main and a post injection. However, the discussion of these three types of injection is beyond the scope of this paper. The results presented in this paper apply to all types of injection.

4 The Interactive Model View

Every simulation begins with a model definition. There are different ways of how such a model can be defined, based on its complexity and the tools used. Many simulation tools allow to compose a model from basic building blocks. Each block has some control parameters and computes a couple of state variables. The blocks are connected and create the joint simulation model. The blocks exchange state parameters with their neighboring blocks (represented by connection lines).

Figure 2 (left) shows a real EUI while Figure 2 (middle) shows a part of the simulation model of that injector. The model was created using the AVL HYDSIM software [2], a 1D CFD simulation tool. It is well suited for the modeling of injection systems, where all flow phenomena primarily occur along lines and valves (1D Flow). The calculations are very fast and the computed results are comparable with much more time-consuming 3D calculations (in case of injection systems).

The engineer carefully chooses the blocks and sets the value of the parameters so that the model represents a real injector as closely as possible. A lot of experience is needed in order to model real injectors (or any other complex device). Each block has several control parameters that can be set, which makes the overall system design very challenging.

Figure 2 (right) shows one of the NCV blocks and its parameters. There is an icon for each block type which helps the engineers to quickly identify a block. Based on the control parameters (determine the block's behavior and characteristics) and the defined model, the simulation software computes the values for the state parameters for each block. Those can be scalar values, but mostly they are time-dependent values, i.e., time series. As we analyze the simulated injection, we are interested in injection over time, usually over one cycle (one full crankshaft revolution [13]).

In the case of multiple simulation runs, the engineer defines the model, first, and then runs the simulation for various combinations of the control parameters. The amount of computed data increases drastically this way. We need advanced tools to support the engineers in the process of analyzing this data. The current state of the art approaches [11, 13] use an interactive visual analysis methodology and complex automatic optimization in order to understand the data.

We use a Coordinated Multiple Views (CMV) system that supports multiple, linked views. A user can choose from over a dozen predefined settings and views or configure all the views and set various parameters, e.g. point size or color, to better display the parameters.

A time-dependent parameter across all simulation runs is called a family of curves. Our CMV system supports this data model and uses the curve view to display a family of curves. The curve view displays all curves in a family simultaneously using transparency to display the density of the curves. When combined with linked views and brushing techniques it can be used to display curves in focus and those forming the context.

Brushing is one of the essential features of every CMV systems [5]. Our CMV system supports both single and multiple (iterative and composite) brushing. The composite brushing enables a user to combine several brushes using Boolean operations in a iterative way. The user selects a Boolean operation to be applied to the current selection and the new brush. The user can easily broaden (OR) or narrow (AND, SUB) the selection in an intuitive way. In the curve view we can use a line brush to select a subset of curves. Similarly we can use an angular brush to select a subset of slopes and the corresponding subset of curves [7].

Although such an approach is of great help for the engineers, there is a problem that the analysis of the results is usually decoupled from the original model. The engineers use different, mostly also linked views to display the results, but there is no notion (except for the labels) of where the results come from (in terms of the corresponding blocks in the model). For example, if an output dimension is called

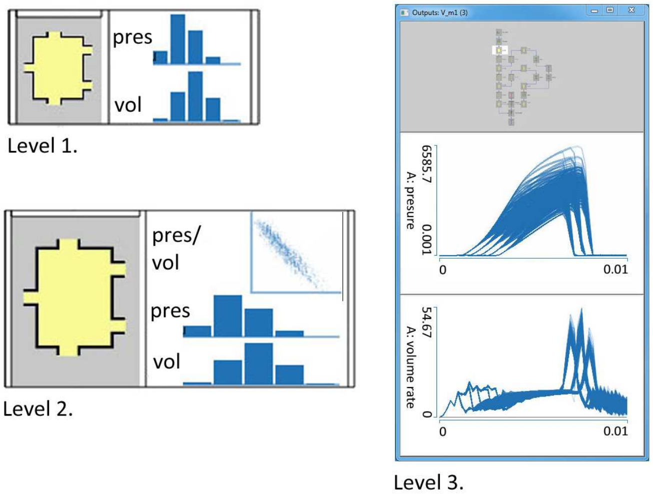

Fig. 3. Three levels of details for representing blocks in the simulation model view. The first level shows only histograms, the second level adds a 2D scatter plot and the third level shows curve views. The space required grows as the level increases, so the third level is shown in a separate floating view.

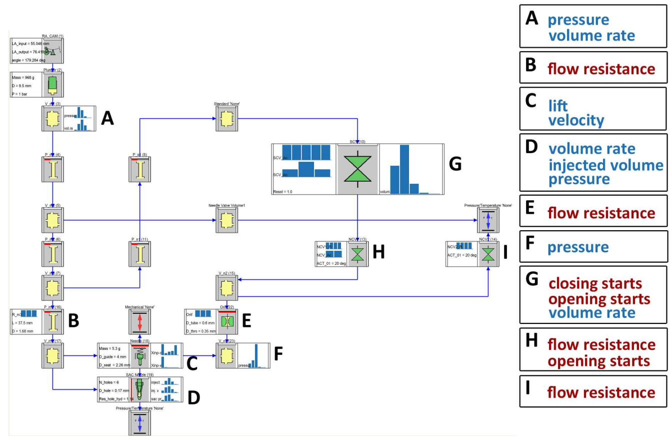

Fig. 4. An example of the simulation model view. We can see all the blocks and their control (red) and state (blue) parameters. The first and second level of details are used.

"volume rate", the engineer has to link it (mentally and by training) to the corresponding valve, nozzle, or orifice.

4.1 Blocks with Three Levels of Detail

In order to close the gap between the simulation model and the simulation data, we propose to integrate the simulation model view into a CMV system. We suggest to enhance the block icons so that they display control parameters and state variables from multiple simulation runs. As the available screen space is very limited, we propose a three levels of detail approach (Figure 3). We have decided to use the left side of the icon for the control parameters and right side for the state variables (Figure 4). We use the three different levels of detail to achieve a compromise between the amount of displayed information and the available space for each block.

4.1.1 The First Level

The control parameters are usually scalar values that can be displayed using a simple histogram. Note that we have multiple runs, which means that the control parameters values can be varied between the simulation runs. The user wants to see which control parameters were varied. Each histogram bin displays the number of runs with a certain value of the respective control parameters. The bins can be equally high (if we run the same amount of runs for each value of control parameters) or they can differ. The constant parameters are simply shown as text. Due to a limited display size we show no more than three parameters at once. The user can easily select which three parameters should be shown.

The right side (showing the values of the block's state parameters) is more complex since state parameters usually have time-dependent values. This means that the results from a single simulation run are already time series. For multiple runs we then have a family of curves, one curve for each run. One possibility of displaying a family of curves is to use a curve view [11]. However, due to a limited display size, it is not possible to show small curve views in a block.

We again use a histogram. We have to aggregate each curve in order to get a scalar value. We allow minimum, maximum, average, and integral aggregates for that operation. The user can select the desired aggregate type for each histogram. Just as on the control parameter side we allow up to three histograms. The user can select which state parameters are shown. Figure 3 shows an example for the first level view where two state parameters are shown, pressure (`press`) and volume rate (`vol`).

4.1.2 The Second Level

At the second level, we double the block size in both dimensions. We have more display area but still there is not enough space to display all curves. Aggregates are used at this level, as well. Since there is a little more space now, the user can choose to show up to twice as many (six) histograms. A smaller number of histograms are displayed in a higher resolution. This depends on the data, the number of parameters, and the task the user wants to solve. Figure 3 shows an example for the second level.

Besides histograms, a scatterplot of two state variables can also be shown. Interestingly, in the presented case the engineer never used this option. In general, we used scatterplots a lot, but we did not want them in the blocks. It was not interesting to see correlation of two state parameters in the same block. We used scatterplots, however, as separate views to compare related state parameters from different blocks.

4.1.3 The Third Level

Due to the limits in the available display area, it is not possible to increase the block size further. Instead, we introduce a new floating view that consists of a map of the model with the originating block and all state parameters displayed using the curve views in a vertical layout (optionally, the user might select a horizontal layout). Figure 3 shows the third level of detail. This is the highest level, i.e. all information is displayed and the user interacts with the curve views. Due to the size of the floating view it is impossible to integrate it in the model view directly.

Therefore, we provide a map as the first view which helps the user to relate it easily to the originating block. The map can be hidden if the user needs more space for the curves. The floating view label remains the only link to the block in this case. The number of state parameters shown are easily set by the user.

Figure 4 shows the interactive model view with the blocks showing their values. Some of the blocks are displayed using the first or the second level of details. The blocks used for analysis (Section 5) are labeled using capital letters **A** through **I**. The corresponding control parameters (red) and state parameters (blue) for the labeled blocks are shown on the right. The interactive model view is fully integrated in a CMV system. This means that the user will use other views (such as scatterplots, parallel coordinates, histograms, curve views, ...) to display selected parameters and to analyze them.

The main idea of the CMV system is to identify some feature in one view (and brush something) and then highlight other parameters from the brushed records in other views, as well as in the enhanced blocks. Figure 5 shows a scatterplot where the user has brushed high average values of block **A** volume rate and low values of block **D** volume rate

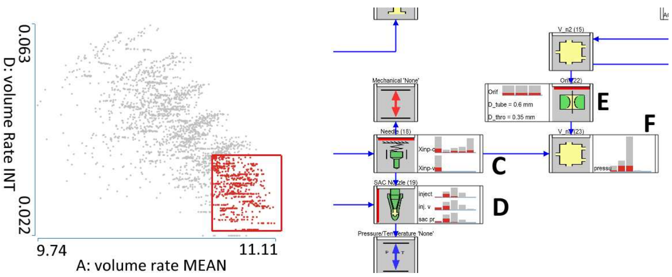

Fig. 5. Whenever the user brushes an interesting subset of the data in any of the views, the simulation model view updates accordingly (being an integral part of the CMV system). Here we can see that the lower right part of the scatterplot (block **D** in Figure 4) has been brushed and all histograms reflect the brushed data in the simulation model view.

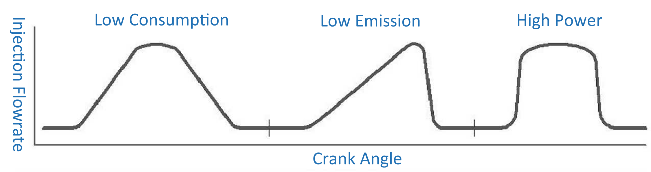

Fig. 6. Ideal injection curves for the low consumption, low emission, and high power modes of operation.

Table 1. Control parameters for the 4,320 possible simulation runs (2,880 simulation runs performed).

Block	Parameter	Values
H	flow resistance	1.0; 2.0; 3.0; 4.0
I	flow resistance	1.0; 2.0; 3.0; 4.0
E	flow resistance	1.0; 2.0; 3.0
B	flow resistance	1.0; 2.0; 3.0
G	closing starts	20; 25; 30; 35; 40
G	opening starts	-15; -20; -25
H	opening starts	-15; -20

Table 2. State parameters used in the analysis.

Block	Parameter	Units
A	pressure	*bar*
A	volume rate	mm^3/deg
G	volume rate	mm^3/deg
C	lift	*mm*
C	velocity	m/s
D	volume rate	mm^3/deg
D	injected volume	mm^3
D	pressure	*bar*
F	pressure	*bar*

integral. The zoom into the model view shows the corresponding values of all control parameters and state parameters directly highlighted in the blocks. The integrated simulation model view helps the user to link the values to the blocks. This way the user better understands the model and related processes.

5 Interactive Visual Analysis of an Electronic Unit Injector

We now describe the use of the proposed approach in the analysis of an EUI. The analysis was done with a domain expert (one of the coauthors) from a company dealing with the development of simulation software and offering services in the car engine design support.

We focus on the shape of the injection curve as generated by an EUI. The mixing process of fuel and air heavily depends on the way the spray develops when injected into the cylinder. The engineers try to shape the injection rate curves in order to achieve desired engine performance. The injector can be tuned for various goals. The three typical modes of operation are low consumption (fuel efficiency), low emission, and high power. Figure 6 shows characteristic injection shapes for these three modes for heavy-duty Diesel engines.

We are interested in how injector points can be adapted to enable the three different engine modes.

In order to understand the injector and to find out about opportunities for improving it with respect to the operation modes, we considered 4,320 simulation runs for different values of the control parameters. Due to some additional constraints introduced by the domain expert, we had a total of 2,880 simulation runs.

The simulation model view introduced in Section 4 was used. The domain expert was mostly interested in flow resistance tuning (this is the most influential parameter for the injector behavior) and we have varied the following flow resistance parameters: the flow resistance for blocks **B**, **E**, **H**. **I**. Furthermore we have varied three parameters controlled by the electronic control unit (ECU), the closing starts for block **G** and the opening starts for blocks **G** and **H**.

Table 1 shows the control parameters and values chosen for each of them. We will explore which factors facilitate or hinder the possibility of achieving the desired form of injection.

In general, the first stage of analysis is experimenting with the injector design and geometric properties. Once these properties are set, injectors are produced and they can not be changed any more. We are not dealing with the physical design of the injector, so it is used as is.

Our point of interest is on hydraulic flows through different parts of injector and correlations between them. During the second stage of the analysis (described in this paper), the designer fixes the geometry and explores the parameters controlled by ECU.

Table 2 shows the outputs (state parameter's values) that have been considered in the analysis. Note that all outputs are time-dependent, i.e., they are not single scalar values but rather functions of time. After we ran all 2,880 simulations we had a dataset consisting of 2,880 records. Each record has a set of independent scalar dimensions (Table 1) and nine dependent attributes which are time series (Table 2). Such a dataset follows a more complex data model than usual data models, where each record has scalar attributes only.

Our first task was to explore possibilities of designing an EUI suitable for high power. Such a scenario is typical when designing high-power special vehicles (military or heavy duty commercial trucks).

5.1 The High Power Mode

If we want to achieve the high power mode of operation, the injection curve has to be shaped almost as a square (steep rise and steep decrease), as shown in Figure 6. Additionally, the injection pressure must be as high as possible in order to inject a sufficient amount of fuel.

We start with the simulation model view (Figure 4). It shows the model with all the blocks and their control parameters and state parameters aggregates on the right.

We are interested to see state parameters values in two blocks, **C** and **D**. We select the third level for the blocks and the curve views are configured. Figure 7 shows only the curve views of interest.

We explore different shapes and try to understand which control parameters combination can produce the desired behavior. We start with the beginning of the injection (needle opening — the point where the injections curves start to rise) and do not analyze the closing (the part where injection curves fall) at the moment.

As stated before, we want very high injection gradient (steep curves) at high injection pressure. High pressure will cause more fuel to be sprayed into the combustion chamber. We brush the curves using the line brush and refine the selection by limiting the crossing angle (Figure 8a). In this way we select only curves which have a fast needle opening.

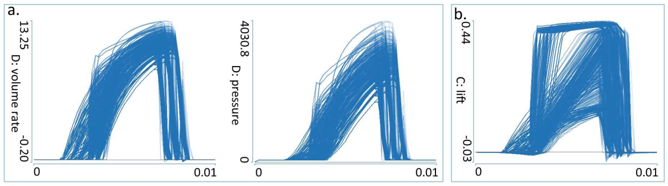

Fig. 7. The third level details for block **D** (a) and block **C** (b). The curve views are used to interactively explore combinations of control parameters.

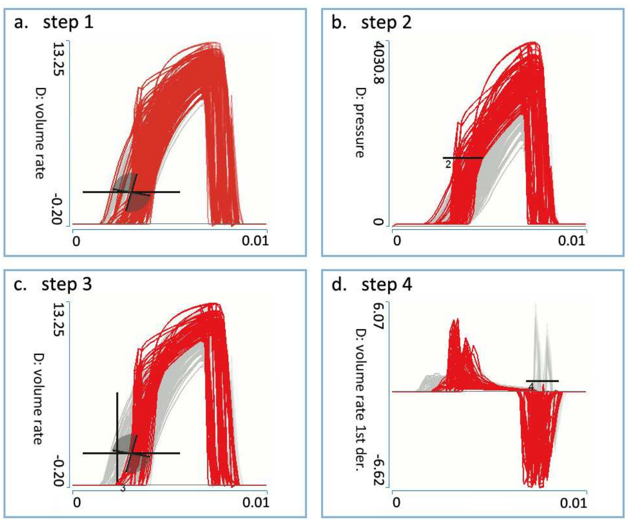

Fig. 8. Searching for the cases with high injection gradient at high pressures (injection rate at opening has steep raise) in four steps — a) step 1: select by limiting the crossing angle on injection rate view; b) step 2: refine the selection with a new brush on the pressure curves; c) step 3: exclude slowly increasing curves by using a difference brush; and d) step 4: exclude the second needle opening by using a difference brush.

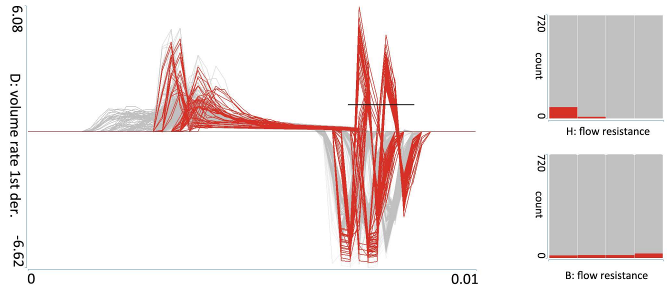

Fig. 9. Eliminating the curves with unwanted, uncontrolled subsequent injection in block **D** using a visualization of the first derivative. The histograms for flow resistance in blocks **B** and **H** are shown.

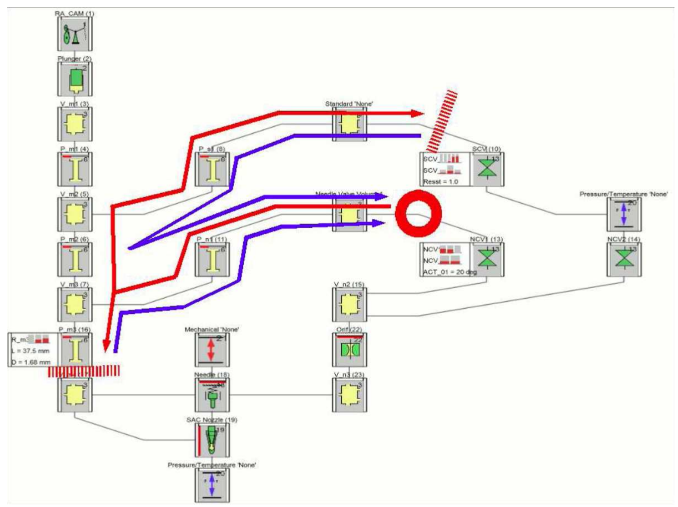

Fig. 10. A shock wave propagates back through the system toward the other side (red line) to block **G** (SCV). Block **G** is not fully open and nozzle inlet has higher flow resistance. Shock waves hit these "hydraulic barriers" and reflect back toward NCV block **H** (blue line).

At the same time, we are interested in cases where injection pressure is high at the beginning of injection. High pressure will cause a stronger penetration of spray into combustion chamber — a desired characteristic of the high power mode. In order to refine the selection, we combined the previous selection with a new brush on the pressure curves (Figure 8b).

Note that we have some slowly increasing curves in the injection rate view. We exclude them (Figure 8c) using a difference brush.

The interactive simulation model view is visible all the time and corresponding control parameters and values of state variables are highlighted during the analysis.

Before analyzing the control parameters causing the desired shape, we want to make sure there is no second needle opening. This is a phenomenon that happens sometimes. The needle is opened once more at the end which leads to an unwanted, uncontrolled subsequent injection. This process must be avoided because it leads to the rapid deterioration of the quality of the combustion process inside the cylinder. In order to examine such cases (not easily visible in the curve view) we used the first derivative of the injected rate curves.

Figure 9 (left) shows the curve views. We can see positive derivative (the left part of the curve view), and negative and positive derivative on the right side of the curve view. However, there are also positive derivatives, i.e., needle openings (the right part of the view). It is the second needle opening, which is not controlled, and has to be avoided. We can brush the unwanted cases (Figure 9).

We know that the moment, when an unwanted behavior happens, is the moment when block **G** (SCV) starts to open but is not fully open and blocks **H** and **I** (NCVs) are already fully open.

Additional investigation of the control parameters that are controlling hydraulic behavior of the system shows that flow resistance in block **H** is small and flow resistance in block **B** is high in the runs where secondary needle opening occurs ((Figure 9 right).

Why does the second needle opening happen? Blocks **H** and **I** (NCVs) are suddenly open and their flow resistance is small. On the other side of valve is low pressure and pressure near the valve drops quickly (Figure 10). That causes a shock wave to propagate back through the system toward the other side (red line) to block **G** (SCV). Block **G** is not fully open and nozzle inlet has higher flow resistance. Shock waves hit these "hydraulic barriers" and reflect back toward NCV block **H** (blue line).

There is again a small resistance toward the control volume. The reflected wave will result in a pressure drop in the control volume and the needle jumps up. The interactive simulation model view is especially useful in analysis of such complex phenomenon where experts have to understand many states of different blocks connected in a certain way.

Once we have analyzed the unwanted behavior we can continue with the original analysis. We will use the difference brush to subtract the unwanted cases from the last stage of the analysis (Figure 8d).

We see that parameters with the dominant influence on the behavior of the system in order to achieve a square shape of injection rate are: the flow resistance within block **E** (orifice), which must be small, and the flow resistance through the passage towards volume above the needle (block **B**) which must be small, too. Less resistance at the nozzle enables a more free and rapid injection start without losses (Figure 11).

On the other hand, the pressure above the needle in the control vol-

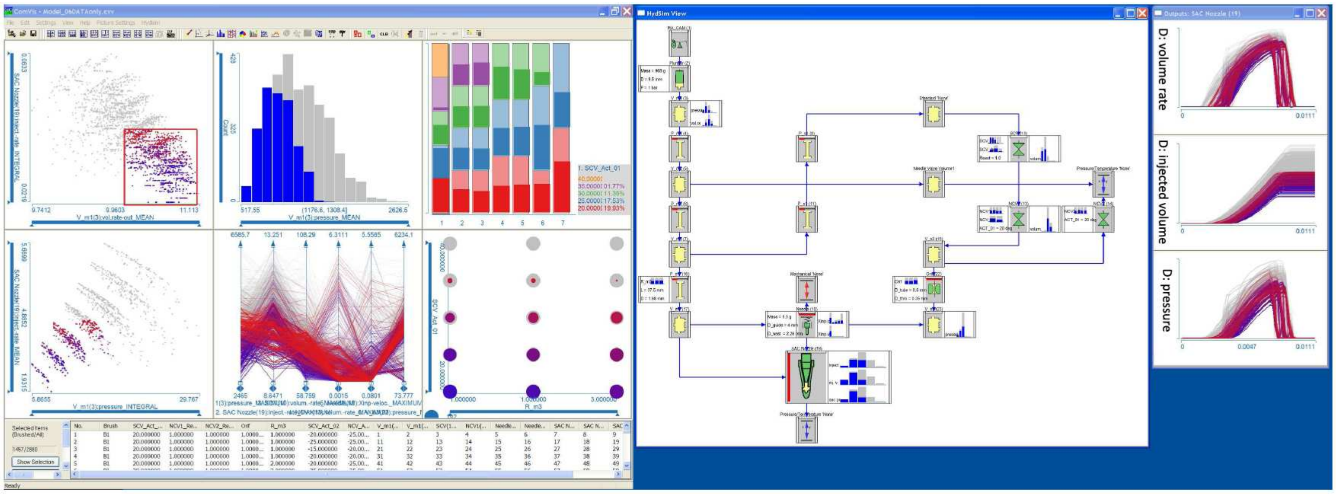

Fig. 12. A snapshot from an interactive visual analysis session with the CMV system as used in this study. On the left, six linked “standard” views are shown with a brush applied to the scatterplot in the upper left. In the middle, the simulation model view is shown with linked histograms, reflecting the same selection. On the right, details for **D** block are shown (as third level of detail view).

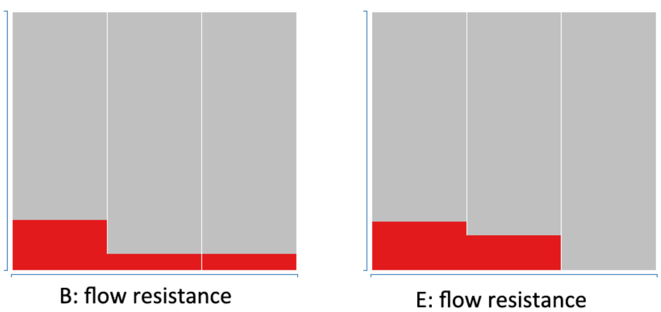

Fig. 11. We can see that the highest block **E** flow resistance values are not allowed if we want maximum power and that there are more combinations having lower **B** and block **E** flow resistance values.

ume will be higher, because there is no damping between the rest of the system and the control volume caused through orifice. When the needle control valve opens, the pressure in the control volume drops faster again, because of less resistance in the orifice. Faster pressure collapse in the control volume will result in a faster needle opening and a faster injection (closer to the square shape).

Besides square shape and high pressure we want a high amount of injected fuel, as well. We focused on block **D** next. We have selected the volume rate through the nozzle, the cumulative volume flow through the nozzle, and pressure in the block **D** as state parameters for this block (Figure 12, right top).

The aggregates of these state variables are displayed in the model view using histograms (Figure 13). The second histogram shows the distribution of the amount of the injected fuel (this is the maximum aggregate) which corresponds to the total amount of fuel injected since injected fuel output is computed as a cumulative value. This is visible when we open the third level and see the curves themselves. If we brush the injected rates now, we can see that they are correlated to the closing start at block **G**.

The second histogram also shows that for the most cases that provide a square shape, the amount of the injected fuel is more or less average. Square shapes of curves are primarily between injection sets in the middle part of the pressure generation curve. It must be so, because for a square shape it is necessary to start with a higher pressure, which causes delay in the start of the injection. The injection is shorter and maximum values of injected amounts are not achieved. The high fuel amount criterion is not fulfilled, but the shape of the curve and

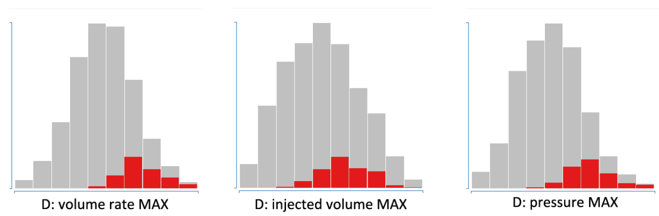

Fig. 13. The second histogram in block **D** summary shows that for most cases that provide square shapes, the amount of the injected fuel is more or less average.

high injection pressure are achieved.

If we select all desirable simulation runs (a square injection curve, high pressure and a significant amount of injected fuel), we reduce our data set to 147 simulation runs (records).

The described example shows us how the engineer starts from the model view, configures the third level views for the analyzed blocks and then selects the curves having the desired shape. Several other views, configured independently from the simulation model view, were used as well.

Figure 12 shows a snapshot of the complete CMV system during the analysis. Some interesting findings (the second needle opening is a nice example for an unexpected finding — *detect the expected and discover the unexpected* [18, 19]) illustrate how interactive visual analysis makes it possible to gain a deeper understanding by supporting additional, non-planned exploration.

5.2 The Low Emission Mode

The emission regulations are becoming stricter every day. Heavy-duty Diesel engines have to meet very strong emission criteria in the near future. The fuel injection system together with the pressure charging, the cooling system, the exhaust after-treatment and other engine subsystems play a key role in achieving low emission.

The fuel injection system has to offer a range of different improvements in areas of flexible injection characteristics, e.g., a multiple injection, high injection pressures and different shapes of injection rates for every regime of operation. The high requirements for heavy-duty engines must be achieved without compromising their current performance and fuel economy. We focus on the emission-reducing capability of a prototype injector in this section.

We start with the model view again, and use it to configure a curve

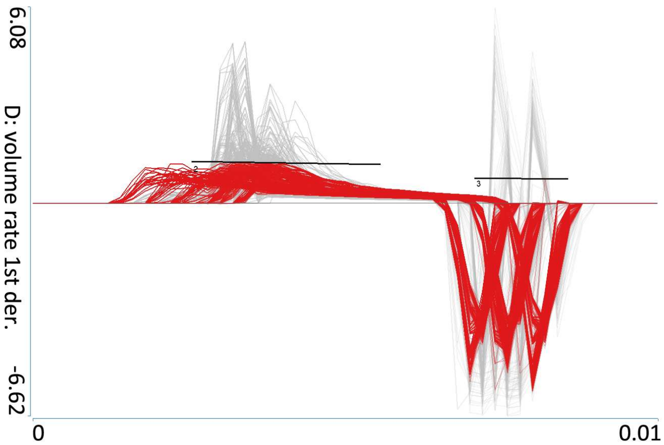

Fig. 14. Using the first derivative of block **D** volume rate, we subtract unwanted curves: those with steep rising and with uncontrolled second needle opening.

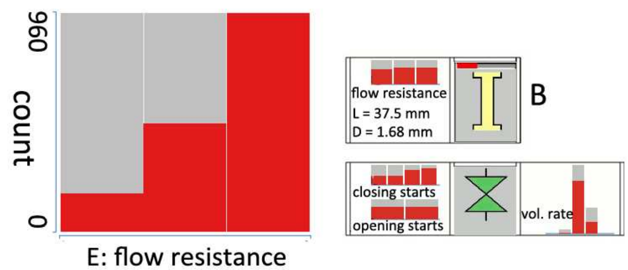

Fig. 15. For a high-power low-emission engine a compromise is needed. Higher block **E** (orifice) flow resistance is welcome but this is in contradiction with the regime of maximum power when as low as possible resistance at this position is needed. Block **B** flow resistance should be low in the high power case and it does not influence the low-emission shape. All values of **B** flow resistance are almost equally probable for the low-emission shape. Block **G** closing starts and opening starts control parameters values make it possible to achieve a sharp or a ramped termination of the volume rate.

view in the CMV system. We want to achieve a different injection profile now, a ramp injection shape for the low emission mode of operation (Figure 6). We use the first derivative of the injection to subtract the unwanted curves: curves with steep rising (high derivative) and curves with uncontrolled second needle opening (undesired behavior). The large number of cases following this shape did not come as a surprise (Figure 14). Due to the physics of the vents and basic injector geometry, the ramp shape is the most natural shape for the unit injector [4, 6].

The model view shows us that the damping at the entrance to the control volume above the needle (block **E**) has a significant impact on the adaptability of the injector to the regime of low emission. Higher flow resistance is welcome but this is in a contradiction with the regime of the maximum power when we need as low as possible flow resistance at this position. Obviously, a compromise is needed if a high-power low-emission engine is a goal (Figure 15).

Let us examine block **B** flow resistance now. Remember it was preferably low in the high power case. We have better luck now, flow resistance does not influence the low emission shape. All values of flow resistance are almost equally probable for all cases with the low emission shape.

We have also analyzed an additional point in the model. We are again interested in checking if it would be possible to tune the engine for low emission and high power. A slow increase of flow resistance

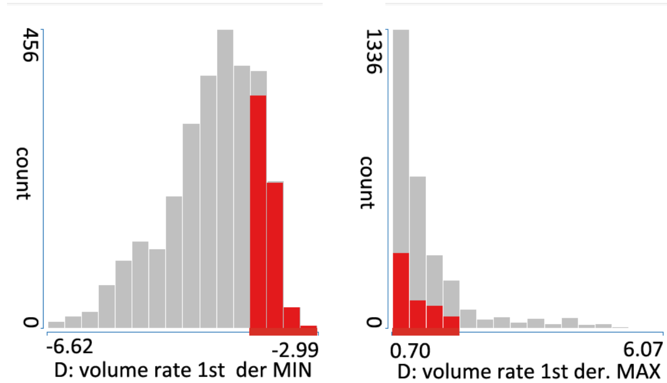

Fig. 16. For the desired shape of the injection curve both gradients of volume rate during needle opening (right) and during the needle closing (left) must be near zero.

in blocks **H** and **I** (NCVs) will result in a better behavior in case of low emission mode but again, this increase is in a contradiction with the high power mode where this control parameter has to be slightly decreased. The domain expert has to find a compromise.

5.3 The Low Consumption Mode

Direct injection systems for Diesel engines must deliver high performance and the maximum torque while keeping fuel consumption low. The desired injection rate shape curve for the low consumption mode of operation is shown in Figure 6.

There are several approaches how to meet the requirement on the injection curve shape. One possibility is to tune the signals sent to blocks **G**, **H**, and **I**. The ECU controls the valves and sends these signals. Different settings of block **G** (SCV) with a constant settings for blocks **H** and **I** (NCVs) may be used at the end of the injection to produce different injection pressure levels during the needle closing. This makes it possible to achieve a sharp or a ramped termination of the volume rate.

Another approach is to see if it can be achieved with altering other control parameters. If we want to have the desired shape of injection curve, the gradients of block **D** volume rate curves during needle opening (Figure 16 right) and during the needle closing have to be near zero (Figure 16 left). As a consequence, the range of values for the volume rate derivation is narrow (approximately between -4 and 2) and the changes in the volume rate are relatively small.

Once we have selected these cases, we can explore the control parameters of the selected simulation runs using brushing (Figure 17).

The large view of block **A** (pump chamber) in Figure 17 shows us that the low consumption regime is some kind of a middle regime. It means that all basic characteristics (like pressure) have middle values (no extreme or limit values). The high power and the low emission modes of operation (Figure 6) are two extreme regimes and the low consumption mode of operation is somewhere in the middle. The low consumption curve shape can also be considered as a combination of the high power and low emission curve shapes.

5.4 Discussion

These three scenarios of interactive visual analysis performed by the domain expert provide a basis for an initial evaluation of the proposed approach. From the domain expert point of view, the challenge is how to understand a complex simulation model with lot of complex interactions among simulation blocks. To achieve that there must be full interaction between the creation of the simulation model, simulation runs and investigation of the simulation results. The process must be fast and transparent.

The advantages of our approach that the model, simulation and results are all integrated within a single application (the CMV system) that provides visual understanding of the simulation process. This, in turns, allows the expert to less effort find an optimal solution with

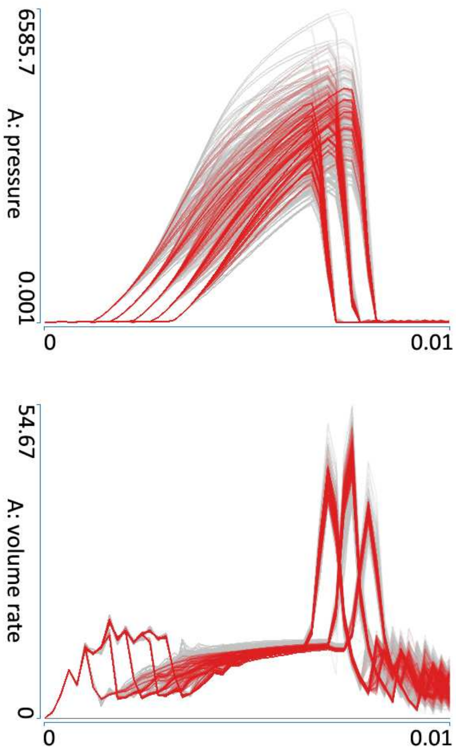

Fig. 17. **A** (pump chamber) block third level. The low consumption regime has all basic characteristics with average values and no extremes.

full understanding of the design. When dealing with multiple simulation runs, the CMV system helps the domain expert to close the gap between the model and data (Section 1), something that has not been available before. Possible improvements include integration of other advanced optimization tools, better support for high-resolution displays, and support for design and analysis of 3D geometry models.

6 Conclusion

Using multiple simulation runs helps engineers to gain a deep insight into the simulated phenomenon. As the model complexity grows it becomes impossible to mentally link the simulation results with the originating blocks of the model. We have integrated a model view into a CMV system and made it possible for engineers to quickly get an overview of the control and state parameters in the model itself. As the space in the model view is very limited we propose a three levels of detail approach where higher levels show more information but require more display area.

The newly introduced interactive simulation model view is fully integrated in the CMV system and a selection in any of the views highlight the information displayed in the blocks. We have illustrated the usefulness of proposed approach in a case study on understanding and tuning an EUI for Diesel engines.

A very positive feedback from the domain expert in the Diesel engine simulation domain (who is also a coauthor of this paper) indicates that such an approach would be useful for other domains as well. Every simulation starts with a model definition and the possibility to show results from multiple runs within the simulation model blocks helps the experts to analyze and understand the underlying system much more efficiently.

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