

# Interactive Visual Analysis Supporting Design, Tuning, and Optimization of Diesel Engine Injection

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## ABSTRACT

Design and optimization of modern, complex systems is unimaginable without simulation. Although the design goals are known in advance, finding an optimal combination of input parameters is a long and tedious task. Simulation of car engine injection systems is a relatively short process. It is possible to run many simulations and then to explore the parameter space. Efficient tools and techniques for parameter space exploration and optimization are needed. We have developed an interactive visual analysis tool, ComVis, and related techniques. We illustrate how ComVis is used to explore the parameter space and to tune and optimize car engine injection systems. The collaboration between domain experts and visualization experts resulted in a new workflow for injection system design, and in development of new, commercially available tools.

## 1 INTRODUCTION

Modern engineering design is practically impossible without simulation. It is easier and cheaper to simulate than to produce real prototypes during the development process. The goals of the engineering design are usually clear at the beginning of the process, but unfortunately it is impossible to determine parameters directly from the goals specifications. The process is always iterative and requires significant domain expert interventions. The parameter space is huge, there are many parameters (tens, hundreds or thousands) for complex systems. Having so many parameters makes any fully automatic optimization method very complex and often impossible to apply directly. Even the systems with only a dozen parameters with complex, non-linear dependencies are already a big challenge to grasp and optimize. Finally, the design goals can be contradictory (for example, low consumption and high power for car engine), and the system designer has to make many design compromises. Interactive visual analysis is a realistic choice as a supporting tool for exploring complex parameter spaces.

We describe how we developed and used ComVis tool [2] in collaboration with domain experts from automotive industry (Figure 1). During our ongoing collaboration (several years now) we have together improved the tool itself and proposed numerous techniques and a workflow for car engine injection tuning and optimization. We were pioneers in applying interactive visual analysis to the injection system analysis and optimization. Based on the case studies described in this paper, AVL List — a company which provides simulation software as well as the measuring systems for automotive industry, developed new tools which follow our ideas. These tools are now a part of the commercially available AVL Workspace suite.

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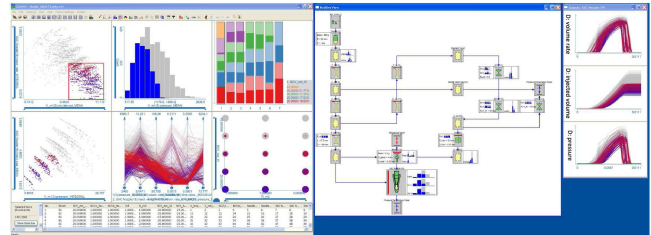


Figure 1: A snapshot from an interactive visual analysis session using ComVis tool. On the left, six linked “standard” views are shown with a brush applied to the scatterplot in the upper left. In the middle, the simulation model view (explained in section 3.3) is shown with linked histograms, reflecting the same selection. On the right, details for the selected block are shown (as the third level-of-detail view).

In this paper we describe illustrative examples from our collaboration that demonstrate the evolution of our approach. We first illustrate how requirements from the domain and complex data led us to the concept of families of curves. We then describe the integration of the simulation model view (starting point for each simulation, and a view domain experts are familiar with) in a coordinated multiple views (CMV) system. Finally, we present how a close coupling of visualization and simulation in an interactive steering loop makes it possible to cope with large and complex systems. Several findings are illustrated in each of those examples.

## 2 INJECTION SYSTEMS

Strict emission regulations and the need to make engines as efficient as possible represent two main constraints in automotive engine design today. 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 unit injector and common rail systems. 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 common rail systems have a common fuel pressurized to the injection pressure in a fuel rail which feeds the injectors. The rail is common to all cylinders.

We analyzed the Delphi E3 Diesel electronic unit injector (EUI) system, 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 EUI has 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. The SCV controls pressure generation inside the pump chamber and the NCV controls whether or not pumped fuel pressure is applied to the upper side of the nozzle needle.

These two EUI valves together have the capability to precisely

control multiple injection events. The needle opening pressure, the injected quantity, the hydraulic separation, and the needle closing pressure depend on how SCV and NCV are activated.

We also analyzed the common rail injection (CRI) system. CRI consists of two parts, hydro-mechanical and electronic. The hydro-mechanical part determines the simulation model, while the electronic part determines the actuator control parameters. CRI can be controlled in a very flexible way. Injection pressure and quantity can be controlled with a high degree of flexibility, multiple fuel injections are possible within one injection cycle, and the time and duration of the injections can be controlled precisely by the engine control unit based on the engine speed and load. These properties are key factors in meeting current and future emission regulations.

### 3 COMVIS TOOL: INTERACTIVE VISUAL ANALYSIS FOR INJECTION ANALYSIS

The parameters selection is a crucial task in the injector design. When we started our collaboration the injector designers used a set of tools which could display results from a single simulation [6]. Numerous graphs (simulation results are time dependent) were depicted using many 2D charts. The designers studied single charts, and compared them for different set of parameters. Injection simulations were done using 1D Computational Fluid Dynamics (CFD) — an abstraction of 3D CFD — which gives sufficiently accurate results but can be computed much faster. During our numerous discussions with domain experts we jointly concluded that interactive visual analysis and a CMV tool might be a right approach. We have generated many simulation runs for different sets of parameters (several thousands of runs at the beginning) and we have stated using our CMV tool — ComVis — to analyze the results. Domain experts simply loved it, but we have discovered many improvement possibilities. During several years we have jointly defined analysis procedures and proposed many improvements of the interactive exploratory process. In this paper we focus on three achievements which illustrate this evolutionary process. These results would not be possible without a close collaboration with domain experts. They are a consequence of complimentary skills of domain experts and visualization experts in the team.

Initially, ComVis supported basic views (scatter plot, parallel coordinates, histogram, ...) with linking and brushing. For each simulation run there is a set of independent parameters which defines the run that produces a set of results. After all the simulation runs were computed (many combinations of parameters) we used ComVis to explore the results, to understand what is going on, and to find a satisfactory set of parameters meeting the defined design goals. Two basic tasks are to see which parameter combinations provide desired results (the domain expert brushes — selects the desired results, and the corresponding parameters are highlighted) and to see how parameters changes influence the results. This is done either by moving a brush in the parameter views or using a gradient color brush. Figure 2 shows an early, basic example where a gradient brush is used to explore what is happening when one parameter ( $R2$ , the ratio between control piston area and the area of the nozzle needle) is increased. We varied six parameters in this particular example. Some of them were varied in more steps, some in less, and we had a total of 19,440 simulation runs. We run simulation for all possible parameter combinations.

The domain experts were very pleased, and we realized we can do much more. It was the first time they could interactively navigate through the parameter space and select a single or a group of runs with specific characteristics.

#### 3.1 First Step - Families of Curves

Exact timing is crucial for an efficient injection process. In order to ensure a smooth and efficient engine run, the injection system has to provide a certain amount of fuel at certain times. The shape of

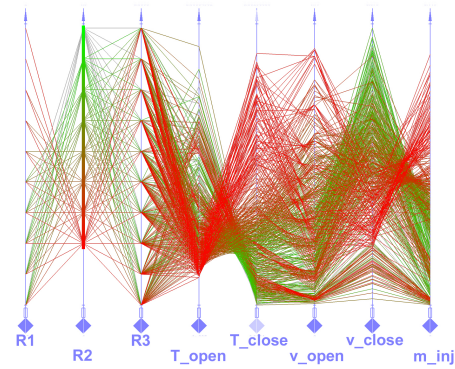


Figure 2: Using a gradient brush in parallel coordinates view to explore an influence of single parameter ( $R2$ ) change.

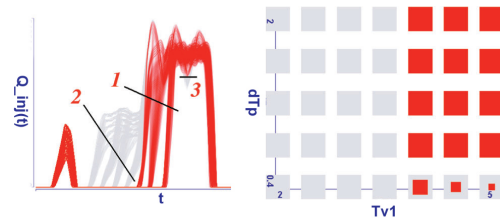


Figure 3: Three line brushes are combined to select the curves with the desired shape. Scatterplot on the right shows the distribution of two control parameters for the selection.

the injection curve is very important, and depending on the operation regime (high power, low consumption, or high efficiency, for example), it differs significantly. We tried to describe curves with a set of parameters, such as injection starting time, needle velocity, etc., but this was not sufficient.

We have extended the conventional data model consisting of records having scalar attributes, to a model where records can have time dependent attributes, too. In this case one attribute, or one cell if input data is considered to be a table, is a function of one independent variable (most often time, but it can also be crank-angle, or some other parameter). Time dependent data might be stored in the conventional way using one column for time. One simulation run would then have more records (time would become another independent variable), and this would not correspond to the nature of data. In order to cope with increased data complexity we introduced the curve view in ComVis [1]. The curve view allowed us to depict all curves belonging to single attribute across all runs (*a family of curves*). We introduced the line brush to select a group of curves.

A line brush is created by drawing a line and all curves crossing the line are selected. Various selections can be combined using Boolean operations. Figure 3 shows a case where three line brushes are used to select curves with the desired shape. The scatter plot on the right shows the corresponding parameters. We have varied five parameters and computed 4,375 runs. Four parameters had five variations and one had seven variations. Again all possible combinations were computed. Note that the scatterplot in Figure 3 depicts two out of five parameters. We see 35 points (five times seven) in the scatterplot. Since we see only two parameters here, and five parameters were varied, each point represents  $4375/35 = 125$  simulation runs. Partially red points show that a particular combination of two parameters was selected out of 125 cases represented by the point. Figure 4 shows an example of a selected range in the parameter space and the curves and other parameters for the selection.

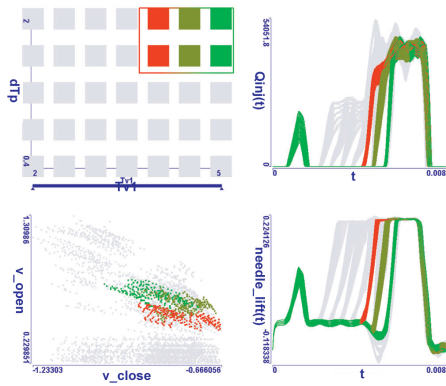


Figure 4: A range in the parameter space is selected to examine the curves and other parameters for the selection.

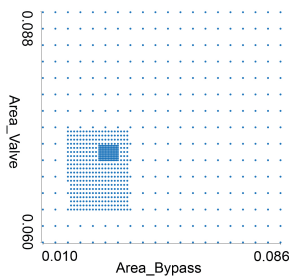


Figure 5: Sampling of the parameter space at different resolutions. Initially, the space was coarsely sampled and additional runs were initiated from the visualization during the analysis process.

### 3.2 Second Step - Simulation Steering

If we want to vary many parameters the resulting data set will be huge. Complex injector models have hundreds of parameters and the number of potential simulation runs is simply too large. We had a common rail injector where we wanted to examine variations of eleven parameters. If we have 10 variations per parameter we need to explore  $10^{11}$  combinations. The computer workstation we used at that time could perform 10 simulation runs per minute. This means it would take  $10^{10}$  minutes to run all the combinations.  $10^{10}$  is 19 000 years! It is clear that we needed something else.

In order to tune the injector we have coupled interactive visual analysis with a simulation tool [4]. We have started from a coarsely sampled parameter space, and analyzed the results. When we identified a region of interest we “ordered” additional simulation runs from the visualization tool. New runs were automatically added to the system as they are computed. However, we went one step further. We did not refine the existing model only, we also changed the model during the analysis process. We started with a simpler model, and extended it during the analysis. Close coupling of simulation and visualization opened new possibilities. We can examine much more complex systems now, and can examine much more parameters. Due to a complex interplay of parameters we often go back and forth as analysis proceeds. Figure 5 shows an example how two parameters were refined during the process. Note that sampling the whole parameter space at the highest resolution would unnecessarily waste computing resources and time. In the proposed way, the domain expert interactively defines regions where additional runs are necessary. Figure 6 shows how the region which contains optimal point changes during the process. As the simulation model becomes more complex and more runs are available, new insights are gained.

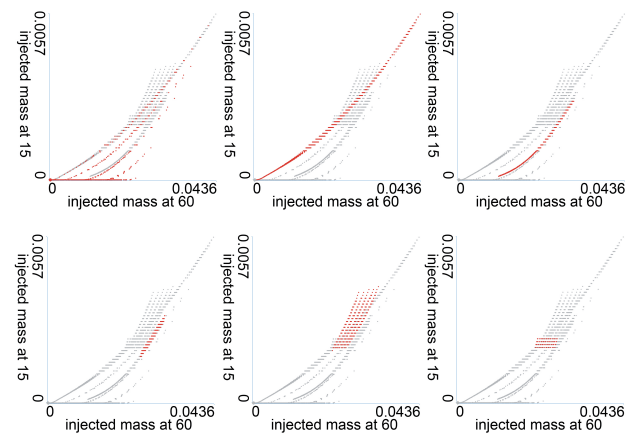


Figure 6: The region containing the optimal point (depicted in red) changes during the process.

### 3.3 Third Step - Model View Integration

Every simulation starts with a model definition. In the case of injection systems, simulation models are defined using a set of available elements (about 50 different elements). A domain expert selects elements and connects them so that they represent a desired injector. The parameters for each element have to be set, some of them are varied over multiple simulation runs. The domain expert only had parameter names and could not see the model view (but was familiar with it) during the analysis. In the case of few parameters it is possible to find names which can be quickly associated with the corresponding parameters and elements. As the number of parameters that are varied increases, it becomes more and more difficult to know where is the parameter in the model.

In order to bridge the mental gap between a parameter name and the corresponding simulation model element we integrated the simulation model view into ComVis [3]. Since there are many parameters per element, and many elements at the same time, we propose a three level approach. At the lowest level three independent parameters (on the left) and three simulated values (on the right) are depicted per element. Small histograms depict these values. At the next level the element of interest is increased and either more parameters are depicted, or larger displays are used for three parameters. At the highest level, new views are automatically configured if the domain expert wants to examine particular parameters in detail.

## 4 IMPACT AND CONCLUSION

Design of modern, complex engineering systems needs powerful support tools. In the case of diesel engine injection design, an advanced simulation tool is available and it is possible to simulate numerous variations of the same model in a reasonable time. The ability to simultaneously explore the results from multiple simulation runs opens new design possibilities. The tools and techniques proposed and developed together with domain experts during the last few years significantly influenced the development of explorative tools for multiple simulation runs at AVL List company.

The introduction of families of curves (Section 3.1) was a significant step forward. Similar data model can be applied to a wide range of problems. We have identified four standard analysis procedures common to a wide variety of problems with families of curves. They are: Black Box Reconstruction, Analysis of Families of Function Graphs, Multidimensional Relations, and Hypothesis Generations via Visual Analysis [1].

We have proposed a workflow for interactive simulation steering (Section 3.2) which can be applied to numerous other scenarios.



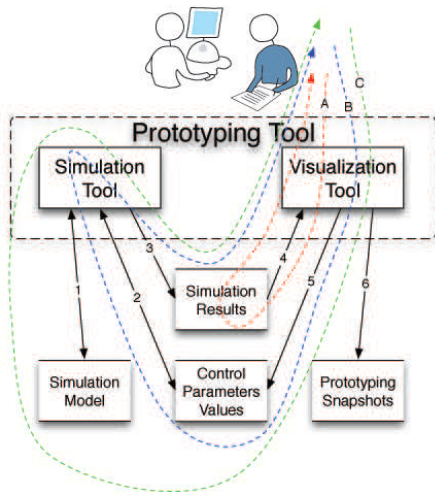


Figure 7: The interactive computational steering workflow.

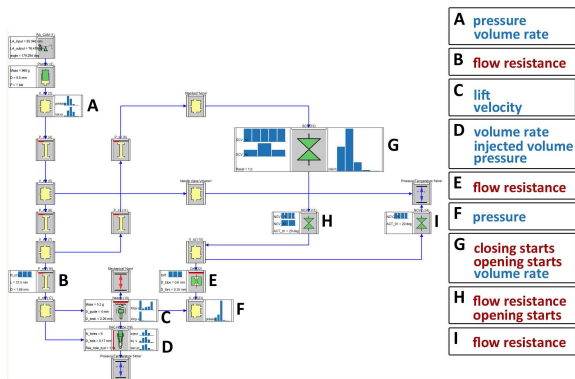


Figure 8: A model used in the analysis with parameters depicted for some elements. Control parameters and simulated values are described in red and blue, respectively.

Figure 7 illustrates three main loops identified. We distinguish three levels of the interactive steering process depicted with loops A, B, and C. The first loop, loop A, is based on the available simulation results. We explore them, get an insight and store the results (snapshots). If this is not sufficient, new simulation results can be generated (loop B). The simulation model is still not changed, only the parameters are being refined. Finally, it is also possible to change the simulation model (loop C). The three loops can be found in any interactive visual steering process.

Integration of the model view (Section 3.3) into ComVis allowed us to explore and tune a Delphi direct unit injector used in heavy vehicles diesel engines. The mental gap which existed before was bridged and the analysis was faster. Figure 8 shows a model used in the analysis with parameters depicted for some elements. Control parameters and simulated values are shown in red and blue, respectively. Figure 9 shows a zoomed in image from the analysis with selected desired values for computed quantities and the corresponding parameter distribution in the model view.

Based on our solutions, AVL developed several packages which are now a standard part of the AVL Workspace suite. The AVL *Impress xD* and AVL *Design Explorer* are specially developed to support tuning and optimization based on multiple simulation runs. The new tools changed the daily workflow and the way engineers design new systems. Domain experts can gain much deeper insight

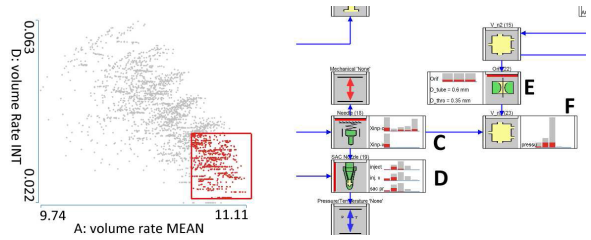


Figure 9: A zoomed in image from the analysis with the selected wanted values for computed quantities. The parameter distribution is shown in the model view.

now and the overall process is much faster. The feedback from domain experts at AVL, as well as the initial feedbacks from AVL customers, are very positive. The described tools and techniques were also used for exhaust system design, timing chain drive design, etc.

We showed how interactive visual analysis supports engineers in understanding complex systems with lot of complex interactions between various parameters. We described three cornerstones in the evolutionary development of our approach and ComVis tool. The development of ComVis and related techniques would not be possible without a close collaboration with domain experts.

Currently we are working on integration of automatic and interactive methods, as this is the most promising way to provide efficient simulation steering for complex systems. We also explore a better support for high-resolution displays, and support for design and analysis of 3D geometry models [5].

## ACKNOWLEDGEMENTS

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