Interactive Visual Analysis in the
Concept Stage of a Hybrid-Vehicle Design

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Abstract
The design of modern, hybrid vehicles is an active area of research. As the whole field is new, engineers need intuitive and powerful support tools. In this application paper, we illustrate an application of interactive visual analysis in the concept phase of a hybrid-vehicle design. We exploit coordinated multiple views to explore and analyze a simulation ensemble – a set of simulation runs of the same simulation model. Once we reduce the ensemble to a single run we use a detailed view, including an energy flow graph and a vehicle drive animation. Very positive feedback from domain experts and opportunities for additional improvements encourage further research.

1. Introduction and Related Work

Strict CO_2 (and other) emission regulations motivate all major car manufacturers to explore alternative vehicle configurations and power solutions. One already proven concept is the hybrid-vehicle idea. The hybrid vehicle has an electric motor in addition to a conventional internal combustion engine. A hybrid vehicle has much more components than a conventional vehicle, including a battery, a special transmission component, and an electric machine (motor and/or generator). The design of hybrid vehicles is an active area of research [LF10, SFK*09, GBF10].

Engineers need support tools to deal with the increased vehicle complexity. As the overall concept is new, previous experiences, based on conventional designs, are certainly useful, but not sufficient to successfully cope with the new requirements.

In this paper, we describe a concrete case where we, a team of visualization and automotive engineering experts, used interactive visual analysis to explore a hybrid-vehicle design in its concept phase. Our study is based on ensemble simulation [KMG*06]. We run many variations of the same model using different sets of control parameters and use a coordinated multiple views system to analyze them. Once we successfully drill down to just a few cases (good ones or bad ones) we use a more detailed visualization for

those cases. The detailed visualization includes 2D charts, as well as a 3D animation of a car model with incorporated data monitors, and the visualization of energy flow shown in the simulation model.

The visualization is integrated within the forthcoming AVL CruiseM [AVL, AVL11] simulation tool, which supports the complete engineers' workflow, including simulation, automatic and interactive optimization and analysis, and reporting and presentation. We focus on interactive visual analysis aspects and illustrate them in our study. The visual analysis approach is especially valuable as engineers gain a much better insight during interactive exploration and visualization compared to purely automatic approaches.

Visual analytics can be defined as the science of analytical reasoning facilitated by interactive visualization [TC05]. Simulation steering and dealing with ensemble simulations requires control over multiple heterogeneous simulation runs. World lines [WFR*10] integrate simulation, visualization and computational steering to deal with the extended solution space by representing simulation runs as causally connected tracks that share a common time axis. In our previous work we provide examples of complex engineering processes [MHSG02] and problems with large parameter spaces [MGJ*10, MGJH11]. Berger et al. [BPFG11] employ methods from statistical learning to predict results in real-

Table 1: *Component parameters which we varied in order to calculate a simulation ensemble.*

Parameter	Used values
Engine	1.0L, 1.2L, 1.5L
Final ratio	3.5, 3.9, 4.3
Vehicle mass	-40kg, Nominal, +40kg
Electric motor	25kW, 35kW, 40kW
Generator	12kW, 15kW, 18kW
Li-ion battery	Standard, Low Temp., High Capacity

time at any user-defined point and its neighborhood. Their techniques guide the user to potentially interesting parameter regions, while showing the uncertainty of predictions using 2D scatterplots and parallel coordinates. Booshehrian et al. [BMPM12] present an interesting parameter space exploration approach from a different application domain.

2. Data and Simulation

The first step in engineering design is the definition of a simulation model. The model consists of different building blocks, each having a set of control parameters. The simulation computes state values for each block once the parameters are set. We vary some parameters and create an ensemble of simulation runs. As we are in the concept phase, we still do not know which car components will be used. However, we do know the main goals, power, torque and inertia requirements that must be fulfilled, as well as vehicle performance, emission and drivability. These requirements are usually in contradiction and optimum search is performed by executing preliminary simulations with optimization.

Figure 1 shows the model used in this paper. The model is a hybrid-vehicle concept model consisting of: gasoline engine, electric generator, electric motor, battery, planetary gearbox, and differential. It is a model of a front wheel drive hybrid vehicle. Table 1 shows which parameters are varied in order to create model variations.

We run a simulation for each combination of the possible values for the six control parameters (2187 simulation runs, 39 hours on a standard PC in total) over a cycle run test on the standard New European Driving Cycle (NEDC) velocity profile (1180 seconds driving cycle). The NEDC helps to compare results from various simulation tools, and measurements from different phases of the design. Figure 2 shows six simulated values: minimum velocity, shifting time, velocity, gear, start signal, and maximum velocity over the cycle (standard engineering chart). Three tests were conducted: the cruising test, the full load acceleration test, and the elasticity test. 2142 simulation runs successfully finished while for the remaining 45 runs the target state (distance and speed) could not be reached (not shown in the paper).

Based on our overall analysis goals we use a subset of the computed results in the analysis: fuel consumption on
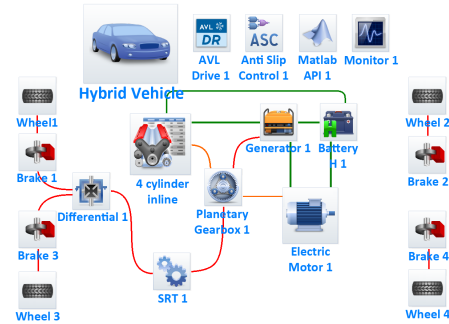

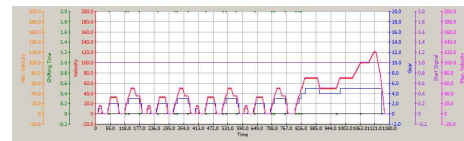**Figure 1:** *The studied AVL Cruise simulation model.*

Figure 2: *A line chart showing six properties during a Cycle run test on the standard NEDC (New European Driving Cycle) velocity profile (1180 seconds driving cycle).*

NEDC cycle (*FuelCons*); fuel consumption in cruising mode (*FuelConsCruising*); full load acceleration (*Acceleration*); engine elasticity (*Elasticity*); state of charge of the battery (*SoC*); and torque behind final ratio component (SRT block in the model in Figure 1) (*Torque*). All results except the *Torque* are scalar aggregates of time dependent results and the *Torque* is a function of time. One record in our data space, which corresponds to one simulation run, contains the set of control parameters from discrete parameter space, a set of scalar results, and a time series representing the *Torque* as a function of time.

3. Interactive Visual Analysis

Once the data is ready we start the interactive exploration. As hybrid vehicles are an area of active research, there are many questions and hypotheses we would like to test. We group the analysis tasks into three categories:

- Parameter reconstruction – find the control parameters corresponding to a desired output.
- Parameter response – what is the output for a certain combination of control parameters.
- Detailed analysis of an individual run.

The tasks from the three groups do not happen sequentially. We often switch between the task groups and go back again. There are numerous "what if ..." questions posted during the analysis, and they can mostly be classified in one of the above mentioned categories. Our main goal is to gain insight into the modeled vehicle and to find a combination of components which provides (in the order of importance): *1)* Low
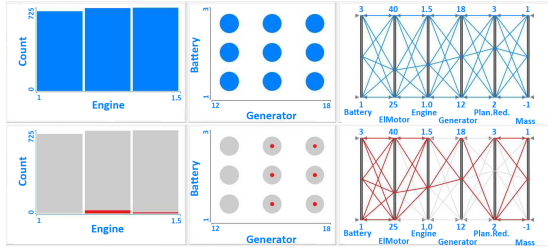
Figure 3: *Histogram, scatterplot, and parallel coordinates, used to depict the discrete parameter space. **Top:** All 2142 cases are shown. **Bottom:** 38 runs are selected. The histogram shows the relation of selected to non-selected (red to gray) parameters (per value). The scatterplot uses point size and color to show the ratio. The ratio is not seen in parallel coordinates, but the view is the most compact.*

consumption, *2)* Good acceleration, *3)* Decent elasticity, and *4)* Torque in the drivetrain behind final ratio (SRT) within the limits of approx. ± 1500 Nm. We use coordinated multiple views to analyze the ensemble. When we drill down (composite brushing) to just a few or a single case, we switch the mode to a detailed analysis of a single run. An excerpt from this analysis is described in the following sections. The whole workflow matches also Shneiderman's visual information seeking mantra "Overview first, zoom and filter, details on demand" [Shn96].

3.1. Overview First

We start with an initial views configuration to depict control parameters, scalar output results, and time series results. Our parameter space is discrete, the electric motor component represents one component available on the market. Although it might be better to use a non-standard motor, it is rarely done due to higher manufacturing and maintenance costs.

We depict the discrete parameter space using histograms, scatterplots, and parallel coordinates. There are 2142 simulation runs, and all of them are depicted. The histograms tend to take a lot of precious screen space, but we can see the distributions of all parameters well. The scatterplots are not well-suited for discrete, overlapping data, but we use them when we are interested in pairs of parameters. Finally, parallel coordinates give us the most compact representation (with many overlapping lines in our case).

We extensively use composite brushing and an in-place focus-plus-context approach where the whole ensemble acts as context and the selected, brushed, simulation runs are in focus. The selection is highlighted using color. Figure 3 shows the three basic views with no runs selected (top row) and the same views where 38 runs are highlighted (bottom row). We see the ratio of the brushed runs for each parameter individually in the histogram and the ratio for a pair of
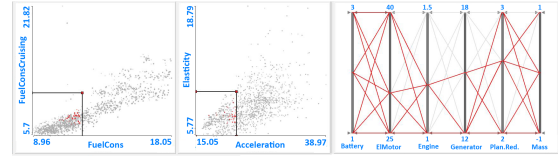

Figure 4: *Desired ranges for* FuelCons, FuelConsCruising *(left), and for* Acceleration *and* Elasticity *(middle) are selected using two brushes. A logical AND operation is applied and possible parameter combinations are depicted in the parallel coordinates view.*
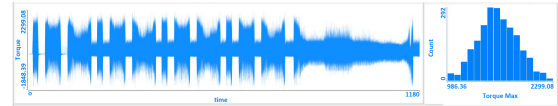

Figure 5: *The curve view shows the* Torque *from all 2142 runs. The user can zoom in to certain areas, and brush the curves using a line brush (not shown). The histogram shows the distribution of the maximum value for each curve.*

parameters in the scatterplot, varying the point size. Finally, we see the relation of all parameters (but cannot see the relative number of brushed runs) in parallel coordinates. One point in a scatterplot represents many runs.

3.2. Zoom and Filter

We use two scatterplots to depict *FuelConsCruising* vs. *FuelCons*, and *Acceleration* vs. *Elasticity*. We select low fuel consumption first (our primary goal), and then good acceleration and a decent elasticity. We use two rectangular brushes in the scatterplots to brush the desired output ranges. Corresponding parallel coordinates show us the subset of the parameter space which fulfills the desired characteristics (Figure 4). All possible values of the parameters are available except for the largest engine and for the largest generator.

We still have many possibilities, and we have not limited the *Torque* yet. Remember that *Torque* is a time series output. The *Torque* curves are shown in a curve view. The curve view shows all curves simultaneously using density mapping in order to cope with overlapping of the curves. We compute the *Torque* maximum aggregate, and use a histogram view to select desired *Torque* ranges. This eases the selection, but the curves themselves are important and we still keep them in the curve view. Figure 5 shows the curve view and the histogram before any case is selected. The ensemble is reduced to four cases by applying several brushes.

All four cases use the 1.0L gasoline engine, a vehicle with the reduced weight (small fuel consumption) and the 12KW electric generator (less power required for powering the generator). This however needs to be taken with caution, as in this test there were no downhill drives, where a generator
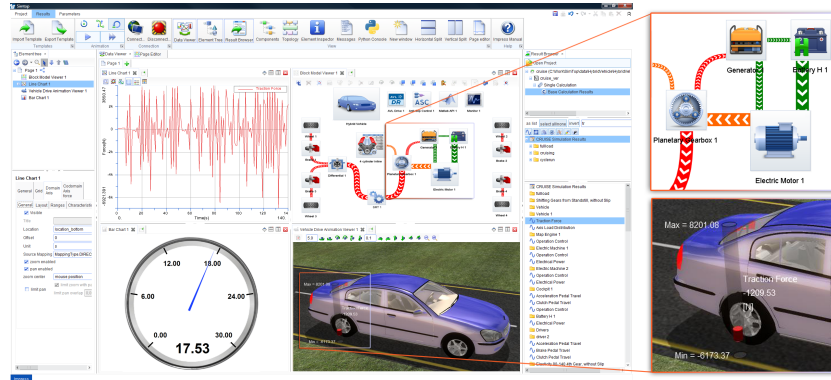
Figure 6: *A details on demand view showing a single curve (upper left), an energy flow graph (upper right), a tachometer (lower left), and the vehicle drive animation (lower right). Two zoomed areas on the right show the EFG and VDA in detail.*

with more power could be utilized to charge the battery, at no additional fuel cost. Although we have reduced the set to four runs only, we still have a variety of choices for batteries, electric motors and transmission ratios. The combination of a lower power electric motor with a high capacity battery (case 1206), or a stronger electric motor with a standard battery (case 1389) is offered. The choice from those combinations could be done taking the price of a high capacity battery into account.

Since the fuel consumption is our main focus, case 1389, in addition to also fulfilling acceleration and elasticity, shows the best fuel consumption performance and presents the good starting point for further, more detailed, vehicle improvements. For the detailed examination we used values for *Planetary Gearbox Ratio* of 3, a 1.0 L *Engine*, *Final ratio* of 3.9, *Vehicle mass* 40kg lighter than nominal mass, *Electric Motor* of 40kW, *Generator* of 12kW, and a standard *Li-ion battery*.

3.3. Details on Demand

Once we drill-down the ensemble to a single run, we switch to a detailed exploration mode and use more advanced visualization. We can do a detailed comparison of several runs next to each other, but the visualization does not scale to hundreds or thousands of runs. Figure 6 shows a screen shot of a possible detailed examination mode configuration for a single run. In this figure, an advanced curve view is used to depict torque, the simulation model view is enhanced by an energy flow graph, the tachometer shows acceleration, and the vehicle drive animation shows a car with traction force of the rear left wheel depicted using a 3D bar. Remember that one run is computed for the whole driving cycle, so this configuration can be animated, or the user can select a point in time for which the results are shown.

The energy flow graph (EFG) (a zoomed portion is shown

in figure 6, top right) is used to visualize the energy distribution within the system. It shows how much energy is transferred between the single components/blocks of the system and how much energy is lost. The energy flow between components is visualized by animated lines showing the direction and magnitude of the energy flow. The line width corresponds to the magnitude. The actual values can be shown as color coded annotations of the block ports on demand.

The vehicle drive animation (VDA) (a zoomed portion is shown in Figure 6, bottom right) is used to visualize simulation results in a context view, showing the whole vehicle in 3D as it moves on the road. Basic parameters are conveyed via animation (speed and route of the vehicle) and user chosen results are visualized (and animated over time) as a 3D bar chart co-located with the appropriate component of the vehicle. This helps the analyst, e.g., to easily see the road slope and correlate various results with driving conditions.

4. Conclusions and Future Work

In this application paper, we show how we use interactive visual analysis in an early stage of a hybrid-vehicle design. We need a combination of two different approaches, coordinated multiple views for an efficient exploration and analysis of thousands of simulation runs, and a more advanced visualization for a single simulation run. The presented results are work in progress and we plan to further enhance the model view. We vary several components and we will use a layered approach in order to show them in the model view. We also plan to improve the energy flow graph and the vehicle drive animation to support multiple simulation runs. We do not expect to be able to show many simulation runs at once using these two specialized views, but we would cover tens of runs, or similar groups of results. The positive feedback from domain experts and first discussions about future improvements show that this is a promising approach.

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