

Definition and Application of a Standard Verification and Validation Process for Dynamic Vehicle Simulation Models

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ABSTRACT

Dynamic system simulation has gained an important role in automotive engineering since powertrains and power management systems are getting more and more complex. The goal is to establish dynamic system simulation as an integral part of the vehicle development process for the purpose of saving development time, improving subsystem and component specifications, and reducing of development cost. A crucial prerequisite for this approach is that the model quality has been identified for the utilized vehicle simulation models. It determines the applicability of the simulation results since the reliability of simulation results cannot be judged without an identified model quality. The identification of model qualities requires an established and standardized verification and validation process adapted to dynamic vehicle simulation, which is introduced in this paper.

The here introduced process for the verification and validation of dynamic vehicle simulation models is structured by certain elements, starting with the definition of unambiguous terms for model validation. It is followed by the description of validation load cases, since the reliability of simulation data strongly depends on the quantity and quality of the load cases and the available reference data that is used for the validation. The introduction of appropriate metrics for the assessment of correlation between simulated data and reference data finally leads to the determination of the model quality for a dynamic vehicle simulation model.

This paper describes a standard validation and verification process and its application to simulation and test data of a fuel cell vehicle system, but the process is defined in a

generic way and, therefore, directly applicable to any dynamic vehicle or powertrain simulation model.

INTRODUCTION

Verification and validation is an important part of the development of system simulation models that is required to judge the simulation results and to understand them in the appropriate relation. Although model verification and validation is a widely discussed topic in the literature (see for instance [1, 2, 3, 4, 5]), a standardized process applicable for dynamic propulsion system models is not available yet. To identify a standardized validation process is of course difficult because each simulation model has its own focus, its own requirements, and its own purpose. Nevertheless, a clear definition of key words discussing the validation of system models and a transparent identification of the model quality are essential parts of a validation procedure.

This paper describes a specific process to be used for validating a dynamic system model of a vehicle propulsion system. Purpose of this process is to determine the model quality in a transparent, reproducible and comparable way. The model quality is described in a validation report that allows the user of a model to judge how well it has been validated. The process is unique for each type of model and model application. The user of the model has to know what has been done to determine the model quality since he must check if the model is appropriate for his intended application.

The first section of the paper gives a general definition of the verification and validation process, explaining the key elements in the right sequence. The focus lies on the validation process that has the goal to determine the model

quality in the end. It is described in a general way how this process is structured and applied and how the model quality can be identified. In the second part, the validation process is applied on a dynamic vehicle model of GM's fourth generation of fuel cell vehicles, the Chevrolet Equinox Fuel Cell vehicle. It is described in an exemplary way how the model quality can be determined comparing simulated signals and reference test data signals for all different load cases.

DEFINITION OF VERIFICATION AND VALIDATION PROCESS

GENERAL DEFINITIONS

First a short definition of important terms will be given. [Figure 1](#) shows the general modeling process, which is similar to the one shown in “Verification and Validation in Computational Fluid Dynamics” [1].

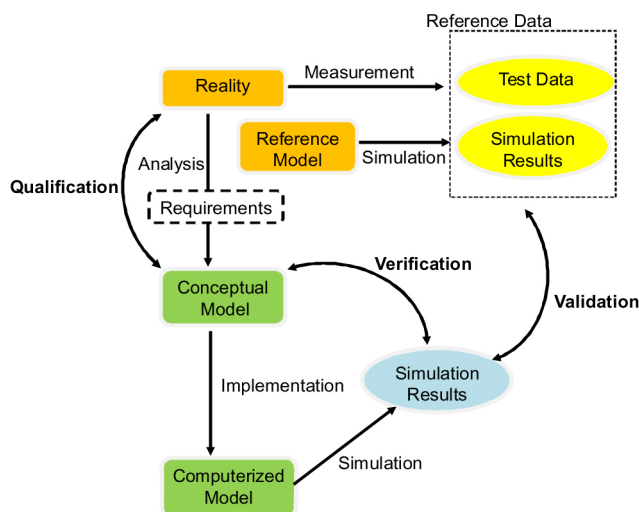


Figure 1. General modeling process (compare [1])

Starting point is a real physical system. From here model requirements are derived that are the basis for the *Conceptual Model*. With the model requirements all requested functionality of the system model is defined describing the behavior of the real system. All system sensitivities, operation ranges, operation modes, and system conditions need to be specified here, that the system model needs to predict and therefore need to be considered within the model. A clear and complete definition of model requirements is essential for the model development and therefore also an important basis for the model verification and validation. The *Conceptual Model* consists of mathematical equations and sketches that represent the model. Since the effort and the runtime of a model increases with the level of detail, a model should not be more detailed than required, matching the needs of the model application. The process of checking the consistency of the *Conceptual Model* is called *Qualification*.

A definition of *Qualification* given by the Society of Computer Simulation (SCS) is as follows [1]:

Qualification: Determination of adequacy of the *Conceptual Model* to provide an acceptable level of agreement for the domain of intended application.

The modeler has to check if all important aspects for the intended use are represented correctly by the *Conceptual Model* using the model requirements as reference. Only if this is fulfilled, the *Conceptual Model* can be implemented using a programming language. The implementation of the *Conceptual Model* on a computer using a programming language or a tool (e.g. Matlab/Simulink [6]) is called the *Computerized Model*. All conceptual drawings and mathematical equations are translated into a program that can be executed on a computer. It is important to note that when using an abstract modeling language like Simulink, the *Conceptual Model* and the *Computerized Model* cannot always be clearly separated.

After the implementation, the *Computerized Model* has to be checked if it correctly represents the *Conceptual Model*. This process is called *Verification*. One definition of *Verification*, which also suits for verification in dynamic system modeling, was given by the American Institute of Aeronautics and Astronautics (AIAA) [1]:

Verification: The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.

The simulation results produced by the *Computerized Model* have to be compared to the awaited outcome of the *Conceptual Model*. This includes checks of the operation range, behavior for extreme input values, checks of mass and energy conservation, and so on. For the purposes described in this paper, it does not include the comparison of simulation data to reference data like data from measurements. The comparison of the simulated data to the reference data from a measurement or a more accurate model is then part of the validation process. The AIAA definition of *Validation* is as follows [1]:

Validation: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

It is determined whether the simulation outcome fits accurately enough the behavior of the real system or of the reference model. A result of the comparison could be that the outcome of the simulation is not sufficient for the intended use. If this is the case, the *Conceptual Model* and/or the *Computerized Model* have to be updated. The following

chapters will give more details about the processes of verification and validation.

VERIFICATION PROCESS

The verification process has two parts: the *Verification Checks* and the *Model Changes*. *Verification Checks* are performed to determine if the *Computerized Model* represents correctly the model requirements and the developer's intention of the *Conceptual Model*. It is important to state that in the verification process described here, no comparison with any reference data is done. The model is checked only for itself if it behaves correctly. The model is checked using various input conditions that depend on the exact type of model. The *Verification Checks* should include the following aspects:

Executability: The first check is if the *Computerized Model* can be interpreted and compiled correctly on the computer and if it is possible to execute it. Syntax errors have to be found, and warning messages from the compiler have to be evaluated. If the compilation, launch time or execution time is too high the model can potentially lose the user's acceptance and can become worthless for its application.

Stability: It should be checked if the model reaches a steady state for constant input signals. This means that all output signals that are expected to reach a steady state come to a constant value after a certain time and do not show unexpected oscillations. Naturally, not all output signals of a model can reach a steady state such as systems with integral behavior. The filling level of a fuel tank for instance will decrease during the whole simulation. Another aspect is unwanted hysteresis effects. If the same steady state is reached one time coming from high load and a second time from low load, the output signals should come to the same level if no hysteresis effect is expected. Otherwise this would be an indicator of an error in the model.

Requirements Check: The output of the model has to be checked regarding the requirements it has been derived from. The model has to be capable of simulating load cases that reflect the system and vehicle behavior defined by the requirements.

Robustness within Operation Range: It has to be checked if the model behaves correctly at the borders of its operation range defined by the requirements. Also for critical combinations of input values and parameters the model has to produce reasonable results. Crossing the operation range of the model must result in a defined behavior, for instance an error message.

Dynamic Behavior: It has to be checked if the model shows a reasonable dynamic behavior on various input conditions. A trivial example for a dynamic vehicle model would be, if the

acceleration pedal is pressed, the vehicle speed should increase and the fuel tank level should decrease

Numerical Solver: The underlying differential equations of the *Conceptual Model* are solved numerically on a computer. This is done using a numerical solver with a certain time step or converge criteria. One aspect that can be checked here is if the model results (the output signals) are independent from the solver that is chosen. The second aspect is the step size that is used. It has to be small enough to achieve a sufficient accuracy for the simulation results but on the other hand, the simulation speed decreases with smaller step size. Also numerical errors are more likely to happen if the step size is too small. Ideally, the step size should be smaller by a factor of 3-5 than the smallest dynamic time constant in the simulated system. If the step size is too small for an acceptable execution time the model needs to be cleaned up from highly dynamic parts that are out of the investigation scope.

Mass and Energy Conservation: For every model that represents physical aspects, the conservation of all properties with an underlying conservation law has to be checked. For a dynamic vehicle model this is especially the conservation of mass and energy. The balance can be made for the whole system but also for every physical subsystem the balances have to be valid. The motivation of the checks is to detect unknown sinks and sources for energy and mass.

If any of the *Verification Checks* show inconsistencies, *Model Changes* have to be performed. These changes can be necessary for the *Conceptual Model* and/or the *Computerized Model*. After the changes, the *Verification Checks* have to be repeated. The result of the verification process is a verified (computerized) model. This model can then be used for producing simulation results to compare with reference data, which is part of the validation process.

VALIDATION PROCESS

The validation process also consists of two elements: The *Data Comparison* and the *Model Adaptations*. The goal is to determine the *Model Quality*. In *Data Comparison*, the simulation results are compared to reference data, which is experimental data or data from a more accurate model. The comparison is made for different *Load Cases*. A *Load Case* is a set consisting of different *Load Case Items*. A *Load Case Item* is the combination of various

- operation ranges regarding the input constraints (e.g. vehicle speed setpoint)
- operation conditions (e.g. ambient temperature)
- operation modes (e.g. initial conditions)

An example for a *Load Case* for a vehicle model is a drive cycle *Load Case* that is a set of different standard drive

cycles, for instance FTP72 and US06 (compare Figure 2). The signals used for the *Data Comparison* need to be defined for each *Load Case*. There is an infinite number of possible *Load Cases*. For complex system models the validation of all possible operation ranges under all possible operation conditions and operation modes is almost impossible, not only because of the huge test matrix required for this. The identification of the *Load Cases*, *Load Case Items* and signals is an important reference for the value of the model validation and their selection has to be based on the kind of the dynamic model, the intended application of the model, and the defined model requirements. The usage of standard driving cycles for instance offers the advantage of comparability, but with the target to validate a dynamic system model not all desired operation ranges, conditions, and modes may be covered.

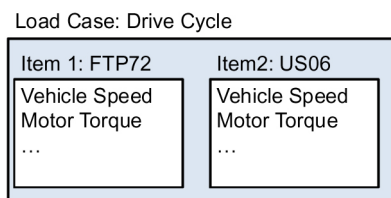


Figure 2. Example for a Load Case with two Load Case Items and a list of signals

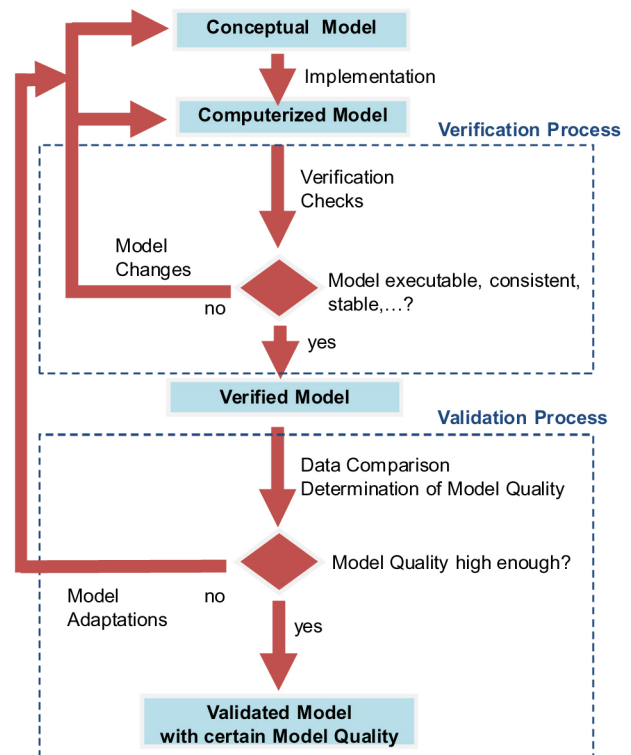


Figure 3. Overview of the verification and validation process

The *Data Comparison* shows how well the simulation results fit to the reference data. Outcome of the *Data Comparison* is the *Model Quality*. If the judgment of the *Model Quality* shows a non acceptable deviation, *Model Adaptations* have to be performed. The model has to be analyzed with respect to reasons for the deviations, and improvements have to be implemented. There can be multiple reasons for deviations. In the *Computational Model*, it could be programming errors, wrong parameterization, insufficient accuracy, and so on. The problem could also originate from the *Conceptual Model*, where the real system is maybe modeled with a wrong approach or in a too simplified way.

After the implementation of *Model Adaptations*, the model first has to go through the verification process again and afterwards, the *Data Comparison* is repeated. The whole process has to be repeated until the *Model Quality* is high enough for the user's intended use of the model, which is identified in the model requirements. The result of the validation process is a validated model of a certain *Model Quality*. Figure 3 shows an overview of the verification and validation process.

MODEL QUALITY DETERMINATION

The *Model Quality* consists of the *Signal Correlation (SC)* and the *Validation Coverage (VC)*. The *Signal Correlation* quantifies how well the simulated and the reference signals match. But the quality of a validation also depends on how many of the *Load Case Items* that have been identified are available. This has to be regarded by defining a *Validation Coverage* in order to have a possibility to judge the significance of a validation.

Signal Correlation

The *Signal Correlation* deals with the compliance of the simulated signals with the reference signals. For each *Load Case Item*, key signals of simulation and reference are compared. The goal is to determine a *Correlation Rating (CR)* for every key signal of a *Load Case Item* using appropriate *Validation Metrics*. The used metric can depend on the *Load Case* that is investigated. The key signals could be for instance fuel consumption or coolant temperature. The *Correlation Rating* is defined on a scale from 0 ("very bad") to 10 ("very good"). How these numbers can be calculated is described in the section about *Validation Metrics*.

In addition, a *Weighting (W)* for the signals is introduced that allows a distinct signal to have a higher weight than another. The *Weighting* is a factor that is multiplied with the *Correlation Rating* of a signal. The *Weighting* factors have to

be defined once for a model and every *Load Case* and may not be changed in different validations. The default value of every signal is $W = 1$.

For calculating the *Signal Correlation* for one *Load Case Item*, the weighted mean value of all *Correlation Ratings* for the signals has to be calculated. For a *Load Case* with N^{items} items and $N^{signals}$ signals to be compared for every item, let $CR_{i,j}$ be the *Correlation Rating* for the i^{th} item and the j^{th} signal and W_j the corresponding *Weighting*. The *Signal Correlation* for item number i is then given by

$$SC_i = \frac{1}{\sum_{j=1}^{N^{signals}} W_j} \cdot \sum_{j=1}^{N^{signals}} CR_{i,j} \cdot W_j. \quad (1)$$

The *Signal Correlation* for the *Load Case* is the mean value of all items,

$$SC^{loadCase} = \frac{1}{N^{items}} \cdot \sum_{i=1}^{N^{items}} SC_i. \quad (2)$$

The total *Signal Correlation* for a validation is finally the mean value for all *Load Cases*. Another possibility would be to introduce a weighting for the different *Load Cases*, but this aspect is not regarded in this paper.

Accuracy of the Reference Data

Another important aspect for the *Data Comparison* in the validation process is the accuracy of the reference data when using measurements. The simulation should predict the required behavior of the real system as good as possible. But the real system is only represented by measurements that have errors depending on different aspects. One is the accuracy of the sensors that are used. Also the mounting of the sensors has an influence on the outcome of a measurement as well as the electronics that is used to analyze the data. All in all, the whole measurement chain has to be taken into account for the accuracy of the data. Since it is not feasible in the practical use to determine the real accuracy for the measurement, the here presented approach is to introduce a *Data Reliability* (DR) factor for every compared signal. The purpose of this factor is that certain signals from the measurement, that are considered to be not usable, can be discarded. The factor can be either 1 or 0. The preset setting is $DR = 1$ for every signal. $DR = 0$ means that the signal is not regarded at all. This could for instance be the case if the signal does not exist in the reference data.

When using a *Data Reliability* factor $DR_{i,j}$ for the i^{th} item and the j^{th} signal, [Equation \(1\)](#) has to be changed to

$$SC_i = \frac{1}{\sum_{j=1}^{N^{signals}} W_j \cdot DR_{i,j}} \cdot \sum_{j=1}^{N^{signals}} CR_{i,j} \cdot W_j \cdot DR_{i,j}. \quad (3)$$

In the *Validation Report*, which will be introduced later, the reliabilities of all signals have to be listed. Therefore it is possible for the reader of the report to see what signals in the reference data did not have sufficient accuracy for the validation. The *Data Reliability* also influences the *Validation Coverage* like described below.

Validation Coverage

In the day to day use, it is most likely that not always all the reference data is available that is specified in the validation process with respect to the requirements and the intended use of the model. For instance, only data from a short steady state run is available for a validation. The result of the model validation can then hardly be compared to a validation where much more test data was available. To handle this circumstance the second part of the *Model Quality* is the *Validation Coverage* (VC). The *Validation Coverage* shows how significant the outcome of a validation is.

The *Validation Coverage* depends on the number of *Load Case Items* that were available for the validation and the *Data Reliabilities* of the signals. It is defined as a percentage value. A value of $VC = 100\%$ means that for all *Load Cases* and *Load Case Items*, which have been identified to cover the required operation ranges, operation conditions and operation modes of the model, all specified signals have been compared with reference data. $VC = 100\%$ does **not** mean that all possible *Load Case Items* having all combinations of operation ranges, conditions, and modes have been used for the comparison. But it expresses that the validation completely covers the operation range in the scope of the intended application field.

The value of the VC is determined for every *Load Case*. For each *Load Case Item*, *Coverage Points* (CP) are introduced. The default value is that every item has $CP = 1$. The current value CP_i of the i^{th} item depends on whether reference data for this item exists or not. If yes, the value is $CP_i = 1$, otherwise $CP_i = 0$. The other aspect affecting the *Validation Coverage* is the *Data Reliability*. If signals are taken out of the comparison since the data cannot be used, the *Validation Coverage* decreases. The percentage value of the *Validation Coverage* for one *Load Case* is then given by

$$VC^{loadCase} = \frac{100\%}{N^{signals} \cdot N^{items}} \cdot \sum_{i=1}^{N^{items}} \sum_{j=1}^{N^{signals}} CP_i \cdot DR_{i,j}. \quad (4)$$

The total *Validation Coverage* for the validation is finally the mean value of all *Load Case* values. In case that a weighting