Development and Demonstration of a Validation Methodology for Vehicle Lateral Dynamics Simulation Models

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List of Abbreviations

Abbreviation	**Description**
ABS	Antilock Braking System
AIAA	American Institute of Aeronautics and Astronautics
CAE	Computer Aided Engineering
CAN	Controller Area Network
CFD	Computational Fluid Dynamics
EDZ	Experimental Data Zone
ESC	Electronic Stability Control
FEM	Finite Element Method
FZD	Institute of Automotive Engineering, TU Darmstadt
ISO	International Organization for Standardization
MVW	Metric Validity Window
NASA	National Aeronautics and Space Administration
OEM	Original Equipment Manufacturer
OS	Overshoot
P/M	Project Management
STM	Standardized Test Maneuver
SWA	Steering Wheel Angle
V&V	Verification and Validation

List of Symbols and Indices

Symbol	**Unit**	**Description**
t	s	Time
ω	rad/s	Cyclic frequency
t_r	s	Rise time
t_d	s	Delay time
t_p	s	Peak time
t_s	s	Settling time
M_{os}	-	Maximum overshoot ratio
C	-	Steady state estimation coefficient
α	-	Uncertainty
v	-	Degree of freedom
N	-	Number of samples
U	misc.	Upper bound
L	misc.	Lower bound
μ	misc.	Mean value
σ	misc.	Standard deviation
C_{xy}	-	Coherence function (between x and y)
G_{xy}	misc.	Cross spectral density (between x and y)
G_{xx}	misc.	Auto spectral density of input
G_{yy}	misc.	Auto spectral density of output
R_{fg}	misc.	Cross correlation function (between f and g)
τ	misc.	Time difference
F_x	misc.	Fourier transformation (of x)
$F_{x,y}$	misc.	Transfer function (between x and y)
$\|x\|$	misc.	Absolute value (of x)
$\Phi_{x,y}$	misc.	Phase angle (between x and y)
Re	misc.	Real part
Im	misc.	Imaginary part
$\bar{x}$	misc.	Mean value of data x

Abstract

In this thesis a validation methodology to be used in the assessment of the vehicle dynamics simulation models is presented. Simulation of vehicle dynamics is used to estimate the dynamic responses of existing or proposed vehicles and has a wide array of applications in the development of vehicle technologies. Although simulation environments, measurement tools and mathematical theories on vehicle dynamics are well established, the methodical link between the experimental test data and validity analysis of the simulation model is still lacking.

The developed validation paradigm has a top-down approach to the problem. It is ascertained that vehicle dynamics simulation models can only be validated using test maneuvers although they are aimed for real world maneuvers. Test maneuvers are determined according to the requirements of the real event at the start of the model development project and data handling techniques, validation metrics and criteria are declared for each of the selected maneuvers. If the simulation results satisfy these criteria, then the simulation is deemed “not invalid”. If the simulation model fails to meet the criteria, the model is deemed invalid, and model iteration should be performed. The results are analyzed to determine if the results indicate a modeling error or a modeling inadequacy; and if a conditional validity in terms of system variables can be defined.

Three test cases are used to demonstrate the application of the methodology. The developed methodology successfully identified the shortcomings of the tested simulation model, and defined the limits of application. The tested simulation model is found to be acceptable but valid only in a certain dynamical range. Several insights for the deficiencies of the model are reported in the analysis but the iteration step of the methodology is not demonstrated.

Utilizing the proposed methodology will help to achieve more time and cost efficient simulation projects with increased model confidence by enhancing the traceability of the validation process.

1 Introduction

Computer simulation models are utilized in nearly every research and product development process as every day tools in automotive industry. Simulation of vehicle dynamics is one of the applications of simulation and modeling in automotive industry that is used to estimate the dynamic responses of existing or proposed vehicles. The simulation of vehicle dynamics has a wide array of applications in the development of vehicle technologies, i.e. active suspensions, chassis design, controller design, driver assistance systems, development of simulators for ergonomics research, etc. Vehicle dynamics simulations reduce the duration and costs during the research and development stages of new designs and technologies.

Although simulation environments, measurement tools and mathematical theories on vehicle dynamics are well established, the methodical link between the experimental test data and validity analysis of the simulation model is still lacking. This thesis aims to introduce a methodology to be used in assessment of vehicle dynamics simulation models.

A simulation model is a mathematical approximation of a real system, which reproduces the whole or certain properties of it. Modeling an existing vehicle can have the purpose of modifying its properties to examine the changes in its responses. Through the examination of the system properties, the effect of new modifications can be verified and the responses can be optimized. The more accurate and reliable the simulations models are the number of real life tests to be performed can be decreased. Sufficiency of accuracy and reliability of a simulation model can be examined by testing the model response against the response of the real system under the conditions which the simulation model is designed for. Through analysis of the real life phenomena to be simulated and the responses of interest, the validation tests and validation criteria can be defined before the development of the simulation model. With the help of these criteria, the examination of the simulation model responses can be standardized and optimized.

1.1 Motivation and Goals

This thesis tries to answer the following questions:

- How can the accuracy or validity of a computer prediction can be assessed?
- What are the main approaches and methods used for validation of vehicle dynamics simulations? What are the shortcomings of the used methods?

- What are the requirements to develop a step-by-step procedure which can determine the validity of a vehicle dynamics simulation more objectively than the today's state of the art?

The thesis aims to describe a top-down methodology which will guide the simulation engineer step by step through the validation process. Starting from the analysis of the real event to be simulated, classification and selection of maneuvers, and examples for procedural assessment techniques will be demonstrated.

1.2 Structure of the Thesis

In this section the outline of the thesis is explained. The theoretical background of the validation is explained in Chapter 2. The philosophical background of validation of simulations, validation of simulation models in general and of vehicle dynamics simulation models in particular are investigated. Several approaches and methods are identified and assessed. In Chapter 3, proposed validation paradigm is explained. The problem is attacked from a top-down perspective, the relationship between the real events, test maneuvers and simulation models are explained. A general validation methodology for vehicle dynamics simulation models based on the validation level of the V-Model is presented. In Chapter 4, the general methodology is individually applied to three test cases. For each maneuver a separate detailed methodology is described. Data handling techniques, validation metrics and their calculation are explained, and results of the assessment are presented and discussed. Chapter 5 summarizes the results of the thesis, speculates on the applicability of the methodology for other vehicle dynamics simulation models with different boundary conditions or for purposes other than vehicle dynamics, and suggests possible future research as an extension to the findings or as remedies to the identified drawbacks.

2 State of the Art

In this chapter, the state of the art is presented. First, the literature on verification and validation of computational models is presented. Simulation models are used in nearly every field of applied sciences, and numerous publications are examined. Definitions of the verification and validation concepts, and approaches to the question from different disciplines are presented. Next vehicle dynamics and the utilization of simulation models in vehicle dynamics are explored. The final part of the literature survey deals with the validation studies dedicated to simulation of vehicle dynamics. Different views and practices are presented and analyzed.

Methodology of the Literature Survey

Validation of vehicle dynamics simulations is an intersection of two fields of study: Simulation of vehicle dynamics, which is a subject of vehicle dynamics, under dynamics discipline of engineering mechanics; and validation of simulations, which is a subfield of computational engineering. Validation of vehicle dynamics is a very well defined and thus narrow field of research. Thus, the search domain is divided and limited to three main subjects: Verification and validation of computational models; validation of vehicle dynamics simulation models in practice; and validation methodologies for vehicle dynamics simulation models.

2.1 Verification and Validation of Computational Models

Using computers to simulate physical events is considered by many as one of the most important developments in recorded history.[1] Starting from the late years of the Second World War, computers have been used extensively in weapon technologies. Today, mathematical models find wide usage in all of the fields of applied sciences.

The question, if the simulation model of a real event faithfully replicates it, is clearly the one of the greatest concerns of the discipline. If the simulation model cannot provide unerring predictions on the outcome of the physical reality, then it is of little value to its users. Therefore, verification and validation of simulation models, often abbreviated as

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[1] Oden (2002): The Promise of Computational Engineering and Science: Will it be kept?

V&V, is an important research field, dominated by computer scientists, CFD and FEM experts, industrial engineers and science philosophers.

2.1.1 Definitions of Concepts of Verification and Validation

Many definitions on V&V can be found in the literature. The most important concept and definitions by various authors are presented in this subsection.

The goal of the V&V is to find out if a model is accurate when used to predict the performance of the real world system that it represents, or to predict the difference in performance between two scenarios or two or more model configurations.[2] The process of verifying and validating a model should also lead to improving a model's credibility with decision makers. Model credibility, being one of the main goals of the V&V, is developing in users the confidence required in order to use a model and in the information derived from that model[3] or simply the decision maker's confidence in the model.[2]

Verification of a simulation model is defined as "Building the model right." in layman's terms.[4] According to Carson,[2] verification is when the model developer exercises an apparently correct model for the specific purpose of finding and fixing modeling errors, and refers to processes and techniques that the model developer uses to assure that the model is correct and matches any agreed upon specifications and assumptions. A simpler definition is ensuring that the computer program of the computerized model and its implementation are correct.[3] Another similar definition is the process of determining if a computational model obtained by discretizing a mathematical model of a physical event and the code implementing the computational model can be used to represent the mathematical model of the event with sufficient accuracy. It addresses the quality of numerical treatment of the model used in the prediction.[5] In the field of computational fluid dynamics, AIAA definition[6] is generally accepted: The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model. In another source concerning CFD applications,[7] verification is defined as a process for assessing simulation numerical uncertainty and, when conditions permit, estimating the sign and magnitude of the simulation numerical error itself and the uncertainty in that error estimate.

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[2] Carson (2002): Model Verification and Validation

[3] Sargent (2010): Verification and Validation of Simulation Models

[4] Pratiksha (2011): Validation and Verification Techniques for Simulation Based Model

[5] Babuska et. al. (2004): Verification and Validation in Computational Engineering and Science

[6] AIAA (1998): Guide for the Verification and Validation of Computational Fluid Dynamics Simulations

[7] Stern et. al. (2001): Approach to Verification and Validation of CFD Simulations

Same richness of definitions can also be encountered for validation concept. Similar to verification, in layman's terms, validation means "Building the right model".[8] One of the earliest publications on the subject defines validation as the process of confirming that the conceptual model is applicable or useful by demonstrating an adequate correspondence between the computational results of the model and the actual data or other theoretical data.[9] Validation can be defined as the total of activities in which the model developer and people knowledgeable of the real system, or a new or modified existing system design jointly work to review and evaluate how a model works, processes and techniques that the model developer, model customer and decision makers jointly use to assure that the model represents the real system (or proposed real system) to a sufficient level of accuracy.[10] Validation is the substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model.[11] It is the process of determining if a mathematical model of a physical event represents actual physical event with sufficient accuracy.[12] It involves a comparison of output data generated by the simulation model with the output data expected from or generated by the real world system.[13] It can also be defined as establishing the range and accuracy of a theoretical model for predicting the behavior of a dynamic system in response to operator commands and disturbances.[14] According to AIAA guidelines,[15] validation is 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. In another source concerning CFD applications,[16] validation is defined as a process for assessing simulation modeling uncertainty by using benchmark experimental data and, when conditions permit, estimating the sign and magnitude of the modeling error itself.

A simple but to the point analogy that depicts the often blurry conception of how a simulation model can be verified but invalid is presented by Logan et. al.[17] The analogy is as follows: Suppose there is a simulation model which uses two values, "2" and "2" as input and reaches the correct answer, "4", through the equation, "2+2=4". Comparing this with the real physical problem, not only should the numerical value of the answer be considered, but also the nature of the problem must be taken into account. If the

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[8] Pratiksha (2011): Validation and Verification Techniques for Simulation Based Model

[9] Schlesinger et. al. (1974): Developing Standard Procedures for Simulation Validation and Verification

[10] Carson (2002): Model Verification and Validation

[11] Schlesinger (1979): Terminology for Model Credibility

[12] Babuska et. al. (2004): Verification and Validation in Computational Engineering and Science

[13] Law (2007): Simulation Modeling & Analysis

[14] Bradley et. al. (1990): Validation of Helicopter Mathematical Models

[15] AIAA (1998): Guide for the Verification and Validation of Computational Fluid Dynamics Simulations

[16] Stern et. al. (2001): Approach to Verification and Validation of CFD Simulations

[17] Logan et. al. (2004): Process and Levels Leading to Qualitative or Quantitative Validation Statements

simulated event in real world was in fact a multiplicative problem (i.e. 2x2=4) rather than an additive one (i.e. 2+2=4), then the simulation model is verified, but invalidated. Verification deals with the results of the equations. Validation deals with the relationship between the nature of the event to be simulated and the equations that try to reproduce that reality.

Absolute validity is refuted by many experts.[18,19,20,21] A model's validity is only defined within the limits of the project and the intended application. Although a more comprehensive validity analysis increases the credibility of the model, it also comes with extra financial and time cost. Thus, a simulation model of a complex system can only be an approximation of the actual system.[20] The logical conclusion is that, no matter how much time is spent to develop, enhance and validate the model, there will always be discrepancies between the physical phenomenon to be modeled and the simulation results.

2.1.2 Philosophical Aspect

According to the presented definitions, validation simply seeks to find out if the simulation model fits the reality and it is unlikely to be of interest to science philosophers, since computer simulation is nothing but the application of scientific theories into computational models.[22] If the computational model describes the mathematical model well (verification) and the mathematical model relates to the theory well (conceptual validation), then the computational model also relates well to the theory; and if the theory is in accordance with the reality, then the computational model is also in accordance with reality (operational validation), provided that the used data is reliable (data validity).

Of the philosophical questions that can be asked, such as "What is reality?" or "How can one be sure of the measurements of reality?", in accordance with the focus and scope of this study, only the philosophical perspectives to the simulation and validation are considered the main question being "Can a simulation model be validated?". This question is actually very similar to one of the main problems of philosophy of science, regarding the scientific progress, and if or when a scientific theory can be accepted to be valid.

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[18] Sargent (2010): Verification and Validation of Simulation Models

[19] Babuska et. al. (2004): Verification and Validation in Computational Engineering and Science

[20] Law (2007): Simulation Modeling & Analysis

[21] Logan et. al. (2004): Process and Levels Leading to Qualitative or Quantitative Validation Statements

[22] Winsberg (2009): Computer Simulation and the Philosophy of Science

As previously stated, pure and absolute validation is impossible.[23] According to Popper,[24] "Scientific theories cannot be proven; they can only be tested through observations." Falsifiability determines if a theory is scientific or not. An agreement of observations with the predictions does not validate the theory, but if one exception is observed, the theory is judged to be invalid. A theory, thus, can never be validated, it can only be invalidated. Therefore, a simulation model can only be invalidated when the performance of the model fails to meet the accuracy criteria and a simulation code can only be unverified when the results fail to reproduce the mathematical model's findings. If the simulation model fulfills the defined validity criteria, then it can be deemed not invalid under the defined specific set of operating conditions and limits and thus can be corroborated.

Different perspectives can be explored through a comparison of the Popperian falisificationist approach with the Quinean holistic perspective and early-period Putnamean realistic pragmatist stance.[25] Popperian falsificationism assumes all scientific theories, or simulation models are invalid, but until they are falsified, they are corroborated. Quinean approach on the other hand speculates that the models lie on a continuum of usefulness, and they can always be revalidated using auxilliary hypotheses or small modifications when they are proven wrong. Putnamean approach emphasizes the realist point of view and states that the simulation models with long records of predictive success are valid or approximately valid.

Thus, it can be concluded that a simulation developer should embrace a Popperian line of thought and accept in advance that the developed simulation model is invalid, and try to prove that it is invalid; since only through invalidation of the current model a better, more advanced model can be reached. An experienced simulation user on the other hand, or an expert customer so to say, is more in the direction of the Quinean approach, trying to reach the best attainable result with the simulation model at hand, and modifying if necessary in the cases when the model's results are falsified by the experimental findings, or in the cases when the model is evaluated at its limits. Putnamean perspective is at best suitable for the inexperienced user, who would opt for a marketed product with in-built simulation models, trusting the long record of predictive success of the commercial software package.

In the current work, a Popperian stance is taken. That is, a simulation model can never be truly valid, since it is only an approximation of reality, and can only be invalidated. Thus, if the tested simulation model cannot be falsified, then it is deemed to be not invalid. Therefore the definition of the term "valid" is "not invalid" in this work.

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[23] Babuska et. al. (2004): Verification and Validation in Computational Engineering and Science

[24] Popper (2005): Logik der Forschung

[25] Klein et. al. (2005): Philosophical Foundations of Computer Simulation Validation

The Popperian falsificationist approach to validation of simulation models is undermined mainly by two behaviors: model cooking and unintentional self deception. Model cooking is when the simulation model is tailored to yield the results “desired” or “expected” by the customer, and unintentional self deception is the faulty analysis of the response data with an eye for the first sign that hints that the simulation is valid, also defined as “student’s syndrome” by Carson.[26] Some of the validation methods are prone to these kind of practices, as is explored in the next section.

2.1.3 Approaches to Verification and Validation

Clearly, views on V&V, how they should be accomplished, and under which conditions can a model be deemed valid are diverse. Different methodologies and perspectives exist on the subject and are presented in this section.

Carson[26] provided a simple framework for validation of production plant simulation models introducing practical techniques and guidelines, and categorization of modeling errors. A “guilty until proven innocent” stance is embraced, the philosophical meaning of which is explored in the following section. It is defended that a model can only be deemed valid if it can serve all the purposes it met within the limits of the depth of the dynamics represented within the model. That is, if a simulation model of a certain dynamical depth provides satisfactory results in the application it is intended for, but fails to deliver valid results for another process for which the necessary model depth it possesses, the model cannot be valid. In the presented framework can be summarized in three consecutive steps as, testing the simulated results for face validity (i.e. if they are reasonable), testing the simulation over a range of input parameters, and finally comparing the simulated results to the reference results (Either from an experiment or from a previously validated model). In this comparison step, the results are compared on a reasonable basis if only one data set is available, and a statistical analysis is performed otherwise.

In the same work, an attempt to categorize the modeling errors is also introduced. Modeling error categories are, project management errors (due to faulty planning and process execution), data and data modeling errors (wrong source of data, wrong assumptions concerning the source of the data or the data itself, human errors during data entry), logic modeling errors (any error inside the coding of the simulation software) and experimentation errors (faulty execution of experiments).

Another approach to the subject is to use the conserved quantities throughout the system for validation.[27] This method uses sampled simulation results to ensure expected behavior during specific times or modes of operation and analyzes models to understand

[26] Carson (2002): Model Verification and Validation

[27] Tiller (2009): Verification and Validation of Physical Plant Models

not just how conserved quantities (momentum, heat, kinetic energy, etc.) flow through the model hierarchy but also whether the model is properly conserving these quantities. This is accomplished through unit testing, in other words solving the V&V problems at the simplest level using simple and well known equations to determine the unit response.

One of the most prolific researchers on the subject, Sargent,[28] suggests four possible approaches to the management and planning of V&V efforts and two different paradigms that relate V&V to the model development processes. In this work, various validation techniques are defined and different aspects of validation, namely conceptual model validity, model verification, operational validity and data validity are explained. A way to document the results is given and accreditation is briefly discussed.

As stated in this work, a model should be developed for a specific purpose (or application) and its validity be determined with respect to that purpose. If the purpose of the model is to answer more than one question, a fully valid model must be able to answer each of the questions satisfactorily. Numerous sets of experimental conditions are usually required to define the domain of a model's intended applicability. A model is considered valid for a set of experimental conditions if the model's accuracy is within its acceptable range, which is the amount of accuracy required for the model's intended purpose. This accuracy requirement should be defined at the start of the development project. However even if a model passes every experimental scenario it is tested against, there is no guarantee that it is valid everywhere inside the domain of application.

The four approaches to V&V management according to Sargent are:

- Subjective decision of the model development team; where the Model development team makes a subjective decision based on various tests and results. This method is prone to model cooking and self deception.
- Subjective decision of the model user (customer); where the user is involved into the development process to determine the validity. Since the user is involved, the credibility of the model is naturally higher than the first method, but still is subjective.
- Independent V&V (IV&V); where a third party runs the V&V work. This approach is very appropriate for large projects with several development teams. It can be performed simultanously with the development, which leads to longer development time since in some cases the development cannot move onto the next step before the previous step is validated; or after the completion of the model, which has its own risks, since any detected error which took place in the earlier parts of the project may lead to extreme delays. This approach, although

[28] Sargent (2010): Verification and Validation of Simulation Models

more costly and time consuming, offers a higher model credibility than the previous two.

- Scoring, where subjectively determined scores for various aspects of the simulation model's performance are assigned. Many examples to this method can be found in the literature.[29,30,31,32] The components and the model can be separately scored. Listing categories for performance measures and scoring the categories to obtain an overall score is another approach. If the simulation model and its components' (or each of the categories') score are above a predetermined pass mark, the model is deemed valid. A possible shortcoming of this technique is that the model might pass the acceptence score, but the overall deficiencies within the model might combinedly deem the model unusable. Also, the definition of the weights and passing scores are highly subjective.

Of the two introduced modeling paradigms, the simpler one[33] is more appopriate for demonstrating the verification and validation inside the model development process. In this paradigm, three main entities are present: Problem entity, which is the physical phenomenon to be modeled, conceptual model, which is the deconstructed and theoretized mathematical abstract of the problem entity, and computerized model, which is the simulation model on a computer. This paradigm is shown in Figure 2.1.

Note that in this work, only the operational validation aspect of vehicle dynamics simulation models is considered.

According to Sargent,[34] validation techniques can be subjective or objective. Statistical tests, mathematical procedures, hypothesis tests and confidence intervals can be counted among the objective techniques. Animation, comparison to other models (or analytical solutions for simple cases), degenerate tests (consistency of the model's intermediate signals), event validity test (comparing the "events" of occurrences of the simulation model to those of the real system), extreme condition tests (unlikely combination of inputs and boundary conditions), face validity (getting expert views on the system behavior for reasonableness), historical data validation and methods (when modeling inexperimentable past events for future prediction like rain fall), internal validity (determining the stochastic variability in the model through several runs of a stochastic model), operational graphics (graphically depicting performance measures), sensitivity analysis (testing several sets of input data and parameters to determine the effect upon the model's output), traces (tracing different intermediate values of the model to

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[29] Logan et. al. (2004): Process and Levels Leading to Qualitative or Quantitative Validation Statements

[30] Balcı (1989): How to Assess the Acceptibility and Credibility of Simulation Results

[31] Gass (1993): Model Accreditation: A Rationale and Process for Determining a Numerical Rating

[32] Gass et. al. (1987): Concepts of Model Confidence

[33] Banks et. al. (1988): Modeling Processes, Validation, and Verification of Complex Simulations

[34] Sargent (2010): Verification and Validation of Simulation Models

determine if the model's logic is correct), Turing tests (experts are asked to discriminate between the experiment and model outputs). Of these techniques, confidence intervals and operational graphics are used in this work for the validity analysis of vehicle dynamics simulations.

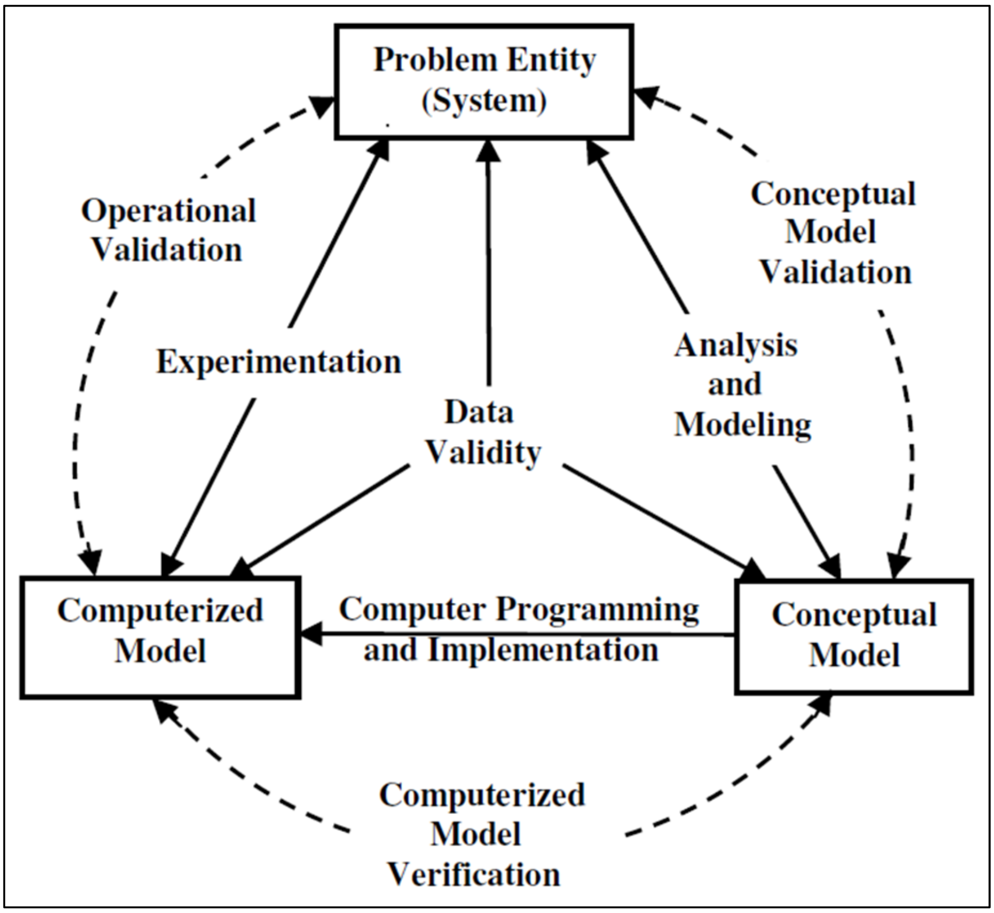

Figure 2.1 Simplified version of the modeling process[34]

A similar scoring approach to increase the credibility of simulation models is developed by NASA.[35] The approach categorizes V&V stages and assesses the exerted effort according to a rigor scale for each of the categories. This creates an easy to handle overview of the V&V work for the decision makers.

Oberkampf et. al.[36] attempted to devise a methodology to construct validation metrics. To this aim, six key features of a validation metric are proposed. According to this study, a validation metric should be quantitative; should include any error resulting from measurements and post processing of experimental data, and numerical operations; should depend on the number of experimental measurements used for testing; should exclude any indications of the level of adequacy in agreement between the simulation and the reality, such as "good", "excellent" or "poor". Validation metrics should be

[35] Blattnig et. al. (2008): Towards a Credibility Assessment of Models and Simulations

[36] Oberkampf et. al.(2006): Measures of Agreement Between Computation and Experiment

measures of agreement, not adequacy or satisfaction. Formulations, methodologies and examples for possible test scenarios are also presented.

For the verification and validation of simulation models, seven rules for model selection and implementation are proposed by Babuska et. al.[37] for solid mechanics finite element simulation models. This approach attacks the root of the validation problem, by first selecting an appropriate, wellproposed mathematical model and then selecting the quantities of interest, statistical tolerances for acceptance accordingly. On the second level an iterative step takes place where the initial findings are used to modify and enhance the model. According to this paradigm, verification is performed independently from the validation. Also impact of the limit imposed by the variety of the obtainable data on the model is explained. Mathematical proof of convergence and the reproducibility of the experimental results are the final two key concepts, that are needed for a healthy validation effort.

Another methodology for finite element simulation models is “A-B-C-D Method”, which defines levels of verification and validation and approaches the problem from a cost-risk analysis aspect.[38] A stands for planning, B stands for solution verification; C stands for model validation and D stands for Model validation extrapolated out of the intended scope of application. This approach introduces a scoring system for different levels of validation, acknowleding that 100% validation is impossible, and the level of attained validation is dependent on the scope of the application. The needed level of validity comes with a cost to attain it, and this cost is analyzed depending on the application. Also, it has been noted during verification and validation analysis, that it is better to use more than one methods simultaneously instead of using one optimal method, since every method has weaknesses and such a practice will remedy these and increase the model credibility.[39]

A research project emphasizing the importance of early V&V of software in mission critical systems and seeking alternatives to formal methods to achieve this goal is realized by Ponsard et. al.[40] A so-called KAOS model is introduced, which implements a goal oriented AND-OR graph approach, consisting of a semi-formal layer for structuring of requirements and test specifications and a formal layer for precise definitions of them, and a developed toolbox, FAUST, is presented.

In a study by Sarin et. al.[41] in 2008, a methodology to construct a metric which is used to compare time histories that are outputs of simulation models to time histories from experimental tests with emphasis on vehicle safety applications was established and

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[37] Babuska et. al. (2004): Verification and Validation in Computational Engineering and Science

[38] Logan et. al. (2004): Process and Levels Leading to Qualitative or Quantitative Validation Statements

[39] Logan et. al. (2005): Comparing 10 Methods for Solution Verification, and Linking to Model Validation

[40] Ponsard, et. al. (2007): Early Verification and Validation of Mission Critical Systems

[41] Sarin et. al. (2008): A Metric For Comparing Simulation Models with Emphasis on Vehicle Safety Applications

topology as a feature to assess models is introduced. The constructed metric incorporates phase, magnitude and topology features in order to quantify the error between the simulation and the experiment. First, phase difference is calculated. Then the data set is corrected using the phase error information, i.e. shifted along temporal axis. This modified data set is used in calculation of magnitude error, and the time derivative of the modified data set is used in calculation of topology error. Also a regression based validation model was proposed which uses this newly developed metric, and tested against other regression models and subjective judgements of experts on the subject.

Romero worked on propagating system uncertainties into the simulation model through model and data conditioning[42] and considers these as an essential step in model validation.[43] The author considers the combined set of somewhat erred equations and associated compensating parameter values, and looks for effectiveness of the combined set, rather than correctness of either or both. Subjective elements and judgment enter into a particular human decision whether to “accredit”, for specific modeling purposes, even demonstrably consistent equation/parameter sets. A model validation activity under representative conditions is pursued to assess and to hopefully affirm the model, the conclusion being that in any real validation experiment, there will be some uncertainty in the values of the actual inputs to the system that is the subject of the model validation inquiry. The logic behind this conclusion is that validation at the conditions of the validation experiment does not, in general, apply to where the model will be used because of the different conditions of operation. Model validation and accuracy criteria are almost always substantially subjective and affiliated pass/fail determinations are not sufficiently robust arbiters of model validity, quality and usefulness. To extract the most value from validation experiments, any model bias and associated uncertainty should be accounted for in prediction. To accomplish this, a methodology to add the uncertainty to the model (best estimate plus uncertainty) to create an augmented or conditioned model that yields total simulation uncertainty that is compatible with the uncertainty of the conditioned experimental data.

Hypothesis testing and Bayesian statistical approaches are also researched as techniques to validate simulation models. An enhanced Bayesian based model validation method together with probabilistic principal component analysis (PPCA) which uses Bayesian hypothesis testing and a quantitative multivariate validation method based on probabilistic principal component analysis[44] and multivariate Bayesian hypothesis testing are proposed for simulation models of dynamic systems.[45] These researches focus on CAE models of automotive safety applications (crash simulation and dummy

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[42] Romero (2008): Type X and Y Errors and Conditioning for Systematic Uncertainty in Model Calibration

[43] Romero (2007): The Need for Model "Conditioning" as Addendum to Model Validation

[44] Fu et. al. (2010): A Study of Model Validation Method for Dynamic Systems

[45] Jiang et. al. (2009): Bayesian Probabilistic PCA Approach for Model Validation of Dynamic Systems

passenger models), but have the potential to find usage in vehicle dynamics as well. Using reversed hypothesis testing to validate methods[46] and employing statistical hypothesis testing as a form of objective cost-risk analysis for validation of simulation models[47] are some examples to hypothesis testing approaches to validation of simulation models. In these approaches, the type II error (false negative), which is the model user's risk in modeling practice, is more critical, since accepting an invalid model as valid will result in user making analysis with an invalid simulation model and can lead to damages (even catastrophic results if for example the simulation model is for a construction project) and special emphasis is placed on minimizing it. Type I error is the model builder's risk, since rejecting a valid model will cost extra work, time and money to the model building party, and does not have the potential to cause any damage.

2.2 Validation and Vehicle Dynamics Simulation Models

2.2.1 Vehicle Dynamics and Modeling

The theory of vehicle dynamics is well established. Since the objective of this study is not to develop a simulation model but to devise and demonstrate a methodology for the validation of simulation models, theory concerning modeling of vehicles is not presented as a separate chapter. In this section, different sources for vehicle dynamics and simulation are named. The simulation model used in the demonstration of the methodology is explained in Chapter 4.

Vehicle dynamics is an area of dynamics and control engineering. Vehicle dynamics study the equations that describe the forces and moments acting on various vehicle components and the response of the vehicle inertial properties to these external forces.[48] The general motion of vehicles are provoked by the horizontal and vertical forces generated on the tire-road contact surface due to the inputs introduced by the driver and the road. These forces are transferred to the body of the vehicle through the suspension, elastic bushings and steering system. When all of these elements are incorporated, this constitutes a high order non-linear system of complex geometric relationships, force elements and viscoelastic components; with many parameters some of which are not directly measurable. Longitudinal performance, lateral stability and handling and vertical ride comfort are the main concerns of vehicle dynamics. Although it is possible

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[46] Hartmann et. al. (1995): Reappraisal of Hypothesis Testing for Method Validation

[47] Balcı et. al. (1982): Some Examples of Simulation Model Validation Using Hypothesis Testing

[48] Allen et. al. (1994): Requirements for Vehicle Dynamics Simulation Models

to decouple longitudinal and lateral components in practice, vertical components do almost always co-act with other components, as roll motion for lateral maneuvers and pitch motion for longitudinal maneuvers.

Simulation of vehicle dynamics has a wide array of applications in automotive industry. They are used in development of new models, modification of existing models, simulators and ergonomics research, development of mechatronic vehicle components are only a few examples. The earliest and simplest vehicle dynamics model is the single track model (also known as bicycle-model), which usually holds for until 0.4 g lateral acceleration.[49] It is still in use today[50] and it can be traced back to 1940.[51] Fundamentals of modern understanding of vehicle dynamics and the description of many important characteristics, such as understeer are presented by Olley[52] in 1946. One of the first vehicle models was proposed by Segel[53] in 1956 for the time domain analysis, and frequency domain response was explored subsequently in the 70's by McRuer et. al.[54]

After the introduction of desktop computers and the exponential growth of the computational power, simulation modeling of vehicle dynamics is an everyday activity. With the emergence of electronic brake systems, such as ABS and ESC, and new technologies enabling exertion of control over many vehicle components in the recent years, complex simulation models have found a new meaning, thanks to their functional advantages (reproducible results, ability to simulate inexperimentable situations, fast application) and financial benefits[55] (reduction of experiment, measurement and prototype costs, early fault detection especially in the cases when a software of more than one components interact, better optimization interface, faster development cycles).

Many textbooks can be found in the literature which explain the fundamentals[56] and advanced applications of different aspects of vehicle dynamics such as tire and brake dynamics,[57] engine and powertrain management,[58] and modeling of vehicle dynamics.[55,59] Lugner and Plöchl's work provides an overview of simulation of vehicle dynamics and model types.[60]

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[49] Ammon (1997): Modellbildung und Systementwicklung in der Fahrzeugdynamik

[50] Diebold et. al. (2006): Einspurmodell für die Fahrdynamiksimulation

[51] Riekert et. al.(1940): Zur Fahrmechanik des gummibereiften Kraftfahrzeugs

[52] Olley (1946): Road Manners of the Modern Car

[53] Segel (1956): Theoretical Prediction and Response of the Automobile to Steering Control

[54] McRuer et. al. (1975): Automobile Controllability – Driver/Vehicle Response for Steering Control

[55] Schramm et. al. (2010): Modellbildung und Simulation der Dynamik von Kraftfahrzeugen

[56] Zomotor (1991): Fahrwerktechnik: Fahrverhalten

[57] Ammon (1997): Modellbildung und Systementwicklung in der Fahrzeugdynamik

[58] Kiencke et. al. (2007): Automotive Control Systems for Engine, Driveline and Vehicle

[59] Genta (1997): Motor Vehicle Dynamics

[60] Lugner et. al. (2004): Modelling in Vehicle Dynamics of Automobiles

One of the main utilization fields of vehicle dynamics simulations is driving simulators. However, vehicle dynamics is only one of the concerns of such a project. Driving simulators must not only model the dynamics of the vehicle accurately, they also must provide correct sensory feedbacks to the driver. An extensive state of the art survey on vehicle simulators by Blana can be found in the literature.[61] Another study by Allen et. al. also provides insight on the prospects of the simulator technologies.[62]

Requirements for vehicle dynamics simulation models are explored by Allen et. al.[63] Their approach stated that a model must be "good enough" but not better; and that the application is what determines the complexity of the model. Ergo, the requirements for any simulation model is application specific. The work emphasizes the importance of an accurate tire model with appropriate depth for the application. The main phenomenon causing the dynamics of vehicles, occur between the tire and the road surface. Therefore tire modeling is one of the most important aspects of vehicle simulations. Without correctly modeled forces, equations of motion governing the motion of the vehicle cannot be solved correctly.

This importance is further explored in another study with comparisons of tire models with different model depths.[64] Tire modeling is a fundamental aspect of vehicle handling dynamics and in order to capture the full range of vehicle stability characteristics, tire models must include the interaction and saturation characteristics of horizontal slips and camber angle, and properly account for the load variation of key parameters. Omission of these effects results in a simplified tire model which excludes roll steer, deflection steer due to compliance and inaccurately calculates individual slip angles of the tires.[65] The effects of different "legal" tires on the same vehicle using fishhook and sine-with-dwell maneuvers are demonstated by Arndt et. al.[66] Up to 33% discrepancy is observed for lateral acceleration gain between two OEM approved tires of the same manufacturer.

One of the most important sources on tire dynamics is written by Pacejka,[67] who also developed the so called Magic Formula, an empirical tire model which relies on curve fitting using experimentally measured tire data, which is also the tire model used in this work. Further work on tire dynamics and tire modeling can be found in literature with different model depths and application scopes. Rill[68] developed a first order analytical

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[61] Blana (1996): A Survey of Driving Research Simulators Around the World

[62] Allen et. al. (2000): Simulation and Measurement of Driver and Vehicle Performance

[63] Allen et. al. (1994): Requirements for Vehicle Dynamics Simulation Models

[64] Allen et. al. (1995): Tire Modeling Requirements for Vehicle Dynamics Simulation

[65] Bundorf et. al. (1976): Cornering Compliance for Description of Vehicle Directional Control Properties

[66] Arndt et. al. (2009): How Tires Change a SUV's Performance in Fishhook and Sine-with-dwell Testing

[67] Pacejka (2005): Tyre and Vehicle Dynamics

[68] Rill (2006): First Order Tire Dynamics

tire model based on Taylor expansion of governing differential equations and another model based on mechanical analogies is proposed by Lacombe.[69] Analytical models which use modal parameters are also present.[70] Physical models, which use FEM to model the mechanics of the tire structure, are very accurate but need substantial computing power. Such models are not suitable for online usage. FTire is a recent example to this model category.[71] The modeling of tire wear is also an important aspect. Tire wear is a major error source in experimentation. Such models have uses in race performance prediction, tire development and fleet management.[72]

2.2.2 Practice of Validation of Simulation Models for Vehicle Dynamics

Many of the publications which claim to present a validation methodology or technique tend to only offer the application of a methodology to a specific case. These types of sources are classified as project specific validation in vehicle dynamics and are explored in this section together with other relevant research on the subject which do not present a validation study.

Salaani et. al.[73] and Heydinger et. al.[74] worked intensively on development, parameter measurement and validation of vehicle simulation models. A multibody full vehicle model is developed, parameters for spring, damper, tire and roll characteristics are measured. Curve fits are generated using these measurements. The performed evaluation covers vehicle directional dynamics that include steady-state, transient, and frequency domain responses. It is concluded that, any detected discrepancy can be caused by a number of reasons including model formulation, programming, parameter identification and experimental procedures; and that the comparison analysis should be supported with analytical reasoning and common sense, which is a subjective approach.

The methodology consists of three main phases: experimental field data collection, independent vehicle parameter measurement and model formulation, comparison of simulation predictions with field data using the same driver control inputs. The importance of independent parameter measurement is emphasized. The model parameters should not be adjusted according to field tests to obtain a match. The comparisons are performed in time domain to check the steady state and low frequency

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[69] Lacombe (2000): Tire Model for Simulations of Vehicle Motion on High and Low Friction Roads

[70] Dihua et. al. (2007): Tire Model by Using Modal Parameters Directly

[71] Gipser (2007): FTire – The Tire Simulation Model For All Applications Related To Vehicle Dynamics

[72] Braghin et. al. (2006): Tyre Wear Model: Validation and Sensitivity Analysis

[73] Salaani et. al. (2007): Parameter Determination and Vehicle Dynamics Modeling for the National Advanced Driving Simulator of the 2006 BMW 330i

[74] Heydinger et. al. (2007): Model Validation of the 2006 BMW 330i for the National Advanced Driving Simulator

responses and nonlinear effects; and in frequency domain to check the high frequency dynamics during transient maneuvers.

The maneuvers are so sequenced; first quasi steady state, then step response, then pulse response (evaluated in frequency domain) and finally a purpose dependent real world like maneuver (lane change in this case) are performed. Sine sweep maneuver would have been an alternative to pulse response maneuver. Confidence intervals are constructed, but no validation criteria are defined using these confidence intervals. Furthermore, no validation metrics are constructed and the validation judgement is taken based on subjective assessments with no quantitative foundations emphasizing the "adequacy" of the simulation model.

Validity analysis can also be employed for evaluation of identified vehicle parameters. The application of genetic algorithm to the physical parameter estimation of a multi-body vehicle model for ride analysis is demonstrated by in a project by Alasty et. al.[75] In this work, the reference data is obtained using a more complicated multibody model. No metrics or statistical analysis are utilized and the validation analysis is executed in time domain, although the simulation model is developed for vehicle ride analysis. This conflict demonstrates the importance of the planning and analysis of the simulation goals.

In another study by McNaull et. al.,[76] a heavy truck simulation model was first modified according to comparison of experimental and simulation results for lateral steady state maneuvers; and then validated for dynamic response using a transient maneuver. The work does not introduce or explain the methodology but rather is a demonstration that the end result of the project is successful. Visual graphical comparison technique is used for validation, but instead of overlaying the graphs, side-by-side placed diagrams are used, which diminishes the credibility of the validation judgement. Also, no metics or statistical analysis are performed. The study demonstrates the correct way of using experimental data to correct the simulation model, by determining the steady state offset and then testing the modified system with a transient maneuver. On the other hand applied validation technique, side-by-side representation of quantities of interests, somewhat lowers the possibility of a healthy call for validity.

Allen et. al.[77] discuss the validation of a full vehicle model in their 2002 paper. The reseach points out the importance of performing the parameter measurements in the targeted operating regime. If the vehicle model is aimed for simulation of limit handling scenarios, such as roll over or tire saturation, the parameter measurements of the subsystems of the simulation model must be accordingly measured, such as the tire data

[75] Alasty et. al. (2002): Genetic Algorithm Based Parameter Identification of a Nonlinear Vehicle Ride Model

[76] Mcnaull et. al.(2010): Validation and Enhancement of a Heavy Truck Simulation Model with ESC Model

[77] Allen et. al. (2002): Validation of a Non-linear Vehicle Dynamics Simulation for Limit Handling

over large slip conditions and higher than normal load, and other non-linearities due to larger deflections caused by the highly dynamical maneuvers.

The addressed validation issues include model formulation, verification of the computer coding, appropriate parameter estimation and measurement procedures and comparison between experimental and simulation results. It is noted that a thorough validation analysis should include both steady state and transient maneuvers, evaluated in both time and frequency domains.

The model is tested using quasi-steady state steering wheel ramp input, pulse response (in frequency domain), double lane change and fishhook maneuvers. Validation metrics or confidence intervals are not used and no statistical analysis is performed. A subjective and qualitative judgement is reached through visual graphical comparison of overlayed time histories of test and simulation results.

This work reflects a correct approach to the validation problem, but with several short comings. The importance of parameter estimation and data validity is well emphasized, and the sequencing of test maneuvers, from steady state to transient and to real life imitating maneuvers, is proper. An alternative maneuver selection for frequency response can be sine sweep, which will have the same power throughout the selected frequency range, contrary to pulse response. However, transient response in time domain is not tested, and no quantitative criteria are set for validation. The validity judgement is taken according to the subjective assessment of the visual resemblance of test and simulation results.

A similar study by Ozan et. al.[78] is a typical example of the bountiful usage of the term "Validation Methodology". In this work a correlation methodology of a multibody simulation model of a commercial vehicle is presented. A three stage process is proposed. First the vehicle´s suspension trimming at static conditions is implemented into the simulation model. The second step is the extensive quasi-static testing of the kinematic components of the suspension and steering system, and their correlation to those of the simulation model. The last step is dynamical testing through linear swept steering maneuver and fishhook maneuver, and visual graphical comparison of the time histories of the experiment measurements and simulation outputs, without any statistical analysis, validation metric or accuracy criteria.

In summary, first the mass and properties, then kinematic modules of the simulation model and finally the whole system response is checked using graphical representations. The explained technique is project specific, and the used methodology to pass validation judgement lacks traceability and objectivity. The reasoning in the selection of maneuvers used in validation of the system's response is not explicit, and the

[78] Ozan et. al. (2010): A Model Validation Methodology for a Commercial Vehicle

assessment criteria is vague. Neither validation metrics nor confidence intervals are constructed.

Another study by Hu[79] demonstrates the development of an analytical half vehicle suspension model for suspension control systems analysis and design. The model is validated based on a comparison of an actual test vehicle's and the model's simulated time domain responses over a particular road event which excites the low frequency band of ride dynamics. The model parameters are first fine tuned using the results from a different experiment. This practice is not advised in general and is only acceptable, if the data used in tuning and validation are different and independent.[80,81]

In this study no validation metrics or statistical analysis are performed. The results of the validation test are evaluated using visual graphical comparison by overlaying time histories of the experimental and model responses on the same plot. However, the suspension, due its highly dynamic nature because of the constantly changing vertical forces and the motion of the unsprung and sprung masses, is a subsystem that should be analyzed in the frequency domain. This work is a good example of an analysis error and demonstrates why the analysis techniques and validity criteria should be defined and documented at the start of the development project.

An approach to the validation problem as a multi-objective optimization exercise is presented by Cassara et. al.[82] Because of the large number of degrees of freedom and tunable parameters of the targeted simulation model, which is a Tractor-Semitrailer model for ride and handling analysis, such an approach is proposed. In order to address this complicated question, modal analysis is performed first at component level and then at subsystem level and then the frequency response of the vehicle system is inspected. Maneuver odometrics are checked as well, and several ride related components are analyzed in the frequency domain. Focus of the research lies on the subsystem interaction and the effect of frequency response modeling accuracy of subcomponents to the total system response considering ride and handling. No criteria are used to quantize the quality of the correlation between the experiments and simulation results. Conclusions underline the importance of frequency domain agreement of the subcomponents in isolating the problem zones in the simulation model.

A vehicle model/simulation evaluation tool for U.S. Army, called Model Post Processor (MPP) is developed by Howe et. al.[83] The tool is capable of comparing different model structures with each other or with actual static and dynamic test measurements for assessment and evaluation. Evaluation of static metrics (mass properties, suspension

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[79] Hu (1993): Experimental Validation of a Half-Vehicle Suspension Model

[80] Heydinger et. al. (2007): Model Validation of the 2006 BMW 330i for the National Advanced Driving Simulator

[81] Heydinger (1990): A Methodology for Validating Vehicle Dynamics Simulations

[82] Cassara et.al (2004): A Multi-Level Approach for the Validation of a Tractor-Semitrailer Ride and Handling Model

[83] Howe et. al. (2008): Development of a Vehicle Model/Simulation Evaluation Tool

kinematics, compliance, etc.) is performed by a consistency check subroutine (CM), and dynamic metrics are checked by another subroutine (DVM) through a range of test maneuvers. Dynamics maneuver range encompasses fundamental tests for longitudinal, lateral and vertical dynamics.

2.2.3 Theory of Validation of Simulation Models for Vehicle Dynamics

The research on methodologies for validation of vehicle dynamics is not diverse. A literature survey performed by Hoskins and El-Gindhy[84] provides an overview of the validation methodology studies for vehicle dynamics models used for driving simulators.

One of the most important works on the subject is the 1990 paper of Heydinger et. al.[85] which is arguably the first study to describe a validation methodology for vehicle dynamics simulation models.

According to this reference, validation is defined as showing that, within some specified operating range of the vehicle, a simulation's predictions of a vehicle's responses agree with the actual measured vehicle's responses to within some specified level of accuracy. This definition emphasizes three points:

- A simulation's predictions may only be correct within some portion of the system's operating range. (e.g. a lateral acceleration range, or a steering angle input frequency interval)
- A simulation's validity is determined for a specified group of inputs and outputs (e.g. a validated lateral dynamics model with suspension degree of freedom is not necessarily valid for comfort studies)
- A simulation's validity is determined according to the variance between the simulation's outputs and experimental measurements.

The described method uses repeated experimental runs at each test condition to generate sufficient data for statistical analysis and generation of confidence intervals to account for the random error in the experiments, in both time and frequency domains. Qualitative and quantitative methods for the comparison of the simulation predictions with the actual test measurements are considered, and visual graphical comparison method is used.

Another method by Garrott et. al.[86], carries on this approach and reapproves the conclusion that a complete validation analysis should be performed in time and

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[84] Hoskins et. al. (2006): Technical Report: Literature Survey on Driving Simulator Validation Studies

[85] Heydinger et. al. (1990): A Methodology for Validating Vehicle Dynamics Simulations

[86] Garrott et. al. (1997): Methodology for Validating the National Advanced Driving Simulator's Vehicle Dynamics

frequency domains. In this work, six maneuver classes are identified and tested. Five of these are identified to be the primary validation maneuvers. These are steady state lateral performance (low frequency cornering), transient lateral performance (maneuvers with a broad range of frequencies at the steering wheel as input), longitudinal acceleration (response to throttle inputs), longitudinal deceleration (response to braking inputs) and road disturbance input maneuvers (suspension kinematics and ride dynamics). The sixth group of maneuvers, designated as "other maneuvers" that attempt to imitate real life situations (double lane change, fishhook, etc.) are not considered among the primary validation maneuvers. A discussion on maneuver classifications can be found in Chapter 3. Contrary to the preceding study,[85] no validation metrics or accuracy criteria are used in this work.

Another approach to the problem is suggested by Bernard and Clover.[87] Three questions are stated to define the validation of a model:

- Conceptual validity: Is the model appropriate for the vehicle and maneuver of interest?
- Verification: Is the simulation based on equations that fully replicate the model?
- Data validity: Are the input parameters reasonable?

It is argued that due to the increasing complexity of modeling practices, it is generally not possible to check all the equations (especially in multibody models) and numerical steps, and running the simulation is the only way for verification.

This method proposes different validation approaches for different model depths. Closed form solutions or estimates and the lateral load transfer measurements are compared with the simulation results for maneuvers lower than 0.5 g which do not involve brake forces. This approach helps finding errors in inertial and geometric parameters, suspension stiffness concerning handling (cornering, aligning, steering, roll, etc.) and load transfer model.

For higher than 0.5 g maneuvers and maneuvers with tire saturation (limit handling), checking the tire forces as a function of kinematics and normal load is advised. This helps detecting the errors in tire model and suspension kinematics.

If the target application for the simulation model involves braking scenarios, checking longitudinal load transfer, wheel slips, longitudinal tire forces and, in the case of braking in a turn maneuver, lateral tire forces assist in finding the errors in longitudinal load transfer, brake and tire models.

This work[87] criticizes Heydinger et. al.[88] for only increasing confidence in the model, but accepting errors as long as the scatter is in acceptable range, which would mask the

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[87] Bernard et. al.(1994): Validation of Computer Simulations of Vehicle Dynamics

[88] Heydinger et. al. (1990): A Methodology for Validating Vehicle Dynamics Simulations

errors that stay within the defined interval. This view is supported with an example case: an incorrect center of gravity height measurement, naturally depending on the amount of error, may provide sufficient results with respect to the confidence intervals for yaw rate and lateral acceleration; but can be clearly detected by checking the lateral load transfer. On the other hand, if a maneuver in which the lateral load transfer plays a significant role is the target of the simulation project, such as fishhook maneuver, center of gravity height, roll angle and lateral load transfer states must be listed among the validation metrics at the start of simulation project. This critic therefore should not be directed to the last stage of the validation procedure, but to the planning stage, where the target maneuver is analyzed and test maneuvers and validation metrics are chosen. The details of this approach are explained in Chapter 3.

Another concern that could yield unreliable simulation results is the fact that the road friction coefficient value supplied to the simulation is most of the time not the same value tested on the actual test field. Determining or calibrating this value using data from the test vehicle taken on the test field or directly implementing the manufacturer supplied values can lead to masked errors.

Concerning the data validity, it is pointed out that faulty data entry is an important risk factor, possible after the reliability of parameter measurements. According to Bernard and Clover, the most dangerous part in data entry of parameter values is tire and suspension data. Both tire model and suspension model have many parameters, and this step is prone to human error.

In a follow up study by Gruening and Bernard,[89] data validity and faulty data entry problematic is further investigated and some examples on the effects of different cases of faulty data entry are demonstrated, although no general methodology to catch such errors is introduced. It is suggested that unreasonable parameters may arise from three sources; erroneous measurements or bad guesses, misinterpretation of the parameters to be measured or mistakes in data entry. Other than obvious recommendation of paying extra attention to data entry and checking for mistakes; a preprocessing procedure is suggested. Running the simulation through a recipe of maneuvers to determine metrics routinely associated with vehicle performance can show some of the simple parameter errors, especially those associated with trim conditions and steady state maneuvers.

For example, vehicles generally have zero degrees of roll deflection at trim conditions. If a simulation is run with straight driving at constant speed on a zero friction surface (thus, trim condition), and roll angle is not zero, of course assuming that the mathematical equations of the model are correct, that indicates that at least one parameter that affects static roll deflection is wrong. However, even in this simple case,

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[89] Gruening et. al. (1996): Verification of Vehicle Parameters for Use in Computer Simulation

there would be more than one likely cause, for example one of the parameters associated with tire geometry or stiffness, or one of the spring rates.

On the other hand, what if parameter data of one of spring rates and one of the tires are mistakenly entered at the same time, in such a way that their effects at trim condition cancel out each other? In this case, a more dynamical maneuver (e.g. steady state cornering), individual load or force measurements for the tires, or an isolated test case would be more practical. In the first two of these suggestions, there is absolutely no guarantee that the simultaneously wrongly entered (or measured) parameters can be identified. Concerning the third suggestion, generally speaking, it is impossible to devise a maneuver which would isolate every parameter of the system since most of the parameters are inherently interacting. One can only come up with a limited number of such maneuvers (for example lateral and longitudinal maneuvers can be separated, but the vertical dynamics almost always affect the other two) but as previously said, there is no guarantee such an error can be detected. Nevertheless this approach is very useful in increasing the model confidence.

Allen et. al.[90] provided a methodical approach to the validation problem. Possible problem areas causing inconsistencies between computer models and real world are described as:

- Mathematical model
- Computational model programming
- Parameter data
- Numerical accuracy and stability

It is advocated that the vehicle dynamics model validation must be considered in context and defined in terms of the domain of useful application, since a simulation model can only be valid up to a degree and a model should be aimed for a certain behavior, and a valid model according to analysis of general system response does not guarantee valid subsystems models.

Validation method presented in this work is summarized in four steps:

- Conceptual validity of the mathematical model
- Face validity (reasonableness) of the simulation model response
- Consistency of input, intermediate and output variables
- Agreement between the simulated behavior and the reference system (real or simulated)

For the validation in the lateral direction, three test cases, steady state cornering, sinusoidal sweep and lane change maneuver, are chosen. The research does not offer a

[90] Allen et. al. (1992): Validation of Vehicle Simulations for Dynamics Stability Analysis

way to assess the findings. Definition of validation metrics, application of statistical methods, or validity criteria are not discussed.

Of these three approaches to validation methods for vehicle dynamics simulation models, Heydinger et. al.[91] and Garrott et. al.[92] focus on operational validity and comparison of test measurements and simulation results; Bernard et. al.[93] and Gruening et. al.[94] recommend analytical solutions and face validity checks for validation and vehicle tests only for parameter identification and error hunt; and Allen et. al.[95] emphasize importance of face validity, analytical solutions and common sense checks with less methodical approach to vehicle testing.

2.2.4 Expert Views on the Subject

In order to extend the state-of-the-art survey to up-to-date applications and practices in the automotive industry, interviews are conducted with simulation experts of three automotive companies. The names of the companies and experts are not explicitly written due to confidentiality issues. Instead, they are represented with letters A, B and C. Company A is a German-American car manufacturing partnership, company B is an American motor company and company C is a leading German automaker.

Company A reported that the validation decision for the simulation models is reached using engineering sense and experience. Maneuvers used in vehicle testing are mostly ISO maneuvers tailored according to the company standards. According to the interviewed expert, only one experiment is performed if the measurement is assessed to be “clean” in on-site analysis. Consequently no confidence intervals are calculated or statistical analysis is performed. Data handling, analysis and documentation are performed using an automated software provided by the corporated R&D division. Only visual comparison of experimental and simulation results is performed and a subjective decision is reached based on engineering sense and cumulative company experience.

Company B follows a methodical approach in assessing the simulation results. It is reported that they follow a classified corporate engineering technical process guideline, which defines measurement and experimentation procedures, descriptions of the maneuvers to be performed, statistical procedures and common metrics. No validity criteria are defined and the subject experts then look for a reasonable fit between the test results and the simulation for validation call.

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[91] Heydinger et. al. (1990): A Methodology for Validating Vehicle Dynamics Simulations

[92] Garrott et. al. (1997): Methodology for Validating the National Advanced Driving Simulator’s Vehicle Dynamics

[93] Bernard et. al. (1994): Validation of Computer Simulations of Vehicle Dynamics

[94] Gruening et. al. (1996): Verification of Vehicle Parameters for Use in Computer Simulation

[95] Allen et. al. (1992): Validation of Vehicle Simulations for Dynamics Stability Analysis

Company C has no worries about model validity, and has full confidence in their in-house developed simulation models. Their approach to experimentation is similar to Company A, that is as long as the response curve does not look abnormal, even only one experiment is regarded sufficient. Thus, no random error fields or statistical procedures are applied for the experimental measurements or for simulation validity analysis. Company C has significant trust in their test drivers' senses and experience, and if a discrepancy cannot be felt by them, it is of no consideration for further analysis. Only visual graphical comparisons of responses are used for validation and no accuracy criteria are defined. Company C places high confidence in collective company experience in assessment of results.

2.3 Conclusion

In this chapter a literature survey on approaches to validation is given. General approaches to the validation problem from other fields of engineering are examined. The validation practices and methodologies in the field of vehicle dynamics are presented.

Conclusions of this chapter are:

- There are many and similar definitions for verification and validation in the literature. One thing nearly all experts agree upon is that an absolute validation is not possible, and validation analysis should be handled according to the needs and limits of the application.
- A simulation model can only be invalidated. Thus, a simulation model that cannot be invalidated, or in other words a simulation model that is "not invalid" is deemed to be a "valid" model.
- Complexity and accuracy requirements of any model are application specific.
- Model tuning is not a recommended practice, but if it is to be performed, it is critical that the data used in tuning must be independent of the validation data sets.
- A vehicle model should be analyzed in time and frequency domain using both steady state and transient maneuvers. Both analyses can show characteristics which may go undetected if only one is used.
- There are basic maneuvers which demonstrate the general dynamics of the vehicle, and then, there are "other" maneuvers, which imitate real life scenarios.
- The most common error sources in validation are inaccurate or inadequate modeling, and data input and measurement errors.
- Inaccurate modeling is the case when an analysis relevant component of the system is not modeled faithfully. (e.g. a vehicle with twist beam suspension is modeled with an independent suspension model.)

- Inadequate modeling is the case when an analysis relevant component of the vehicle is not included in the model. (e.g. a model developed to investigate lateral dynamics should include nonlinear effects of the suspension kinematics)
- Data validity, although not directly influencing the structure of the simulation model, plays a colossal role in the outcome of the validity analysis. Data validity may be compromised by wrong measurements or data entry mistakes. Either way, there is no standard method to identify these mistakes.
- Consistency checks are recommended to detect the errors, although it is casually possible that two errors can interact in such a way that they can mask each other.
- There is no standard in experimentation and data handling processes in vehicle dynamics modeling.
- There is no standard reasoning process in the vehicle dynamics modeling application in validation analysis. Most of the applications rely only on visual comparison and subjective judgement. Diagrams types used in visual comparison also do not follow any recognizable pattern and their contents and structure are determined at will by the research team. Most of the time, the team which developed the model also decides if the simulation is valid. This whole process chain diminishes the credibility of these models.
- Existent works on validation methodologies for vehicle dynamics simulations focus on different aspects of the question.
- There is no identified methodology in application which encompasses the whole development process of vehicle dynamics modeling. From a bottom-up perspective; the validation criteria are dependent on the application, validity metrics and data handling are dependent on the chosen maneuvers and analysis, maneuver selection is dependent on the targeted real life phenomena to be simulated. Thus, a methodology which attacks the problem from a top-down approach is required.

3 Proposed Validation Paradigm

In this chapter, the proposed validation paradigm is explored. First the real events, and their relationship with the simulation practice are investigated. Test maneuver classifications are introduced. The system development system V-Model is explained and the validation level of the V-Model is analyzed from a vehicle dynamics point of view. Finally, a validation methodology for the validation of vehicle dynamics simulation models is introduced. The application of this methodology to specific maneuvers is explained in the next chapter.

3.1 Analysis of Real World Maneuvers

Vehicle dynamics in reality consists of complex maneuvers, which are dependent on many factors:

- Road/environment conditions
- Subjective perception of the driver (conditions-perception conflict, perception speed in maneuver, perception-decision-reaction time)
- Subjective skills of the driver (skill-goal conflict leading to wrong input introduction for a certain intended trajectory, actuation speed, actuation accuracy)
- Goal of the maneuver (avoidance, overtaking, emergency brake, avoidance and emergency brake, avoidance and overtaking, accelerating turn, constant radius constant speed turn in a ramp/slope, reaction to loss of control due to an unforeseen event, etc.)

Driver, under the influence of sensory feedbacks from vehicle (visual feedbacks such as engine speed, vehicle speed, visual warning elements; auditory feedbacks such as engine sound, vehicle noise, auditory warning elements; haptic feedbacks such as seat or steering wheel vibration, steering hardness, other), passive environment (any environmental element that does not directly interact with the dynamics of the vehicle; light condition, road properties that are still in visual field of the driver, like an oncoming curve or a speed bump or a child running after a red ball, auditory elements), active environment (any environmental element that interacts with the dynamics of the vehicle like temperature, road conditions, humidity, air quality), perceives and evaluates, and decides upon a desired trajectory (intention), and makes corrections on the vehicle control interfaces (steering wheel, throttle, brake pedal, clutch, gear selection, etc.). Inputs from the control interfaces activate relevant actuators, and interaction of these actions with the active environment elements change the dynamic state of the vehicle.

Changes in the dynamics of the vehicle do not affect the environmental factors directly (an exception being tire road surface interaction), but change the sensory inputs from the environment (active and passive) to the driver as well as the state of interaction between the active environmental elements and the vehicle. This interaction is summarized in Figure 3.1.

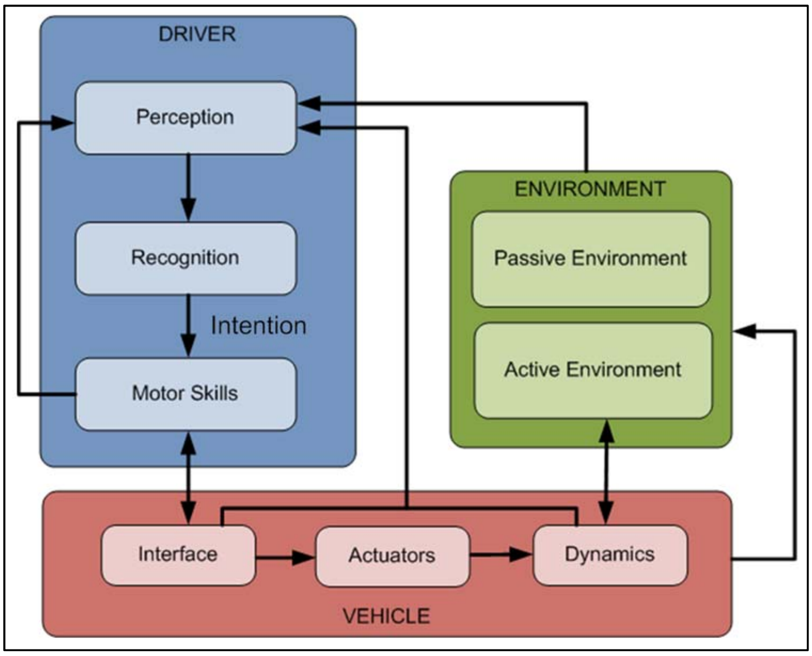

Figure 3.1 Vehicle handling in real life maneuvers

This scheme is actually very similar to the driver model devised by Donges[96,97] although similar approaches are also present.[98] The resultant maneuver is not what is in mind of the driver, but rather the result of the interaction of all of the elements explained in the above system. It is clear that, not every driver will react at the same speed to the sensory inputs, reach the same desired trajectory or make the necessary corrections at the same quality.[99] But a general assumption can be made that they will reach the same intention (i.e. overtake, avoid the pedestrian, etc.) for the sake of validation of vehicle dynamics simulations purposes, since the decision algorithms, psychological processes and ergonomics are out of the context of this study. Bottom line is that the maneuvers in real life are intention driven.

[96] Donges (1982): Aspekte der Aktiven Sicherheit bei der Führung von Personenkraftwagen

[97] Winner et. al. (2009): Handbuch Fahrerassistenzsysteme, p. 15

[98] Schramm et. al. (2010): Modellbildung und Simulation der Dynamik von Kraftfahrzeugen

[99] Weir et. al. (1978): Correlation and Evaluation of Driver/Vehicle Directional Handling Data

The main goal of the simulation practice is to predict the outcome of these events. However, the simulation model cannot be tested using these maneuvers, because of the general ambiguity in the definition of the maneuvers. Hence, not only must the simulation possess certain qualities to predict a given real world event or maneuver, but also the maneuvers to assess the quality of the simulation must also be able to reproduce the most important aspects of the maneuver. These maneuvers are the test maneuvers.

The test maneuvers, although executed in real world, do not possess the same properties of the actual real world maneuvers. They exhibit the same non-linear high order coupled dynamics as the vehicle would show in every day maneuvers. However, firstly, they are not intention driven. The characteristics of the time histories of the inputs are either predefined (open loop case) or dictated by the test track (as in double lane change[100]) or the magnitude of one of the system variables (as is in the fish hook maneuver[101]). Moreover, the feedback to the driver (other than the control feedback, e.g. the driver must see the track to follow it in double lane change maneuver) does not matter in the execution of test maneuvers. Passive environment also has no effect whatsoever on the outcome, since the sensory feedback to the driver do not change the way the maneuver is performed. A summary of this case is presented in Figure 3.2, where the difference in effects of environment and some of the driver's function are shown.

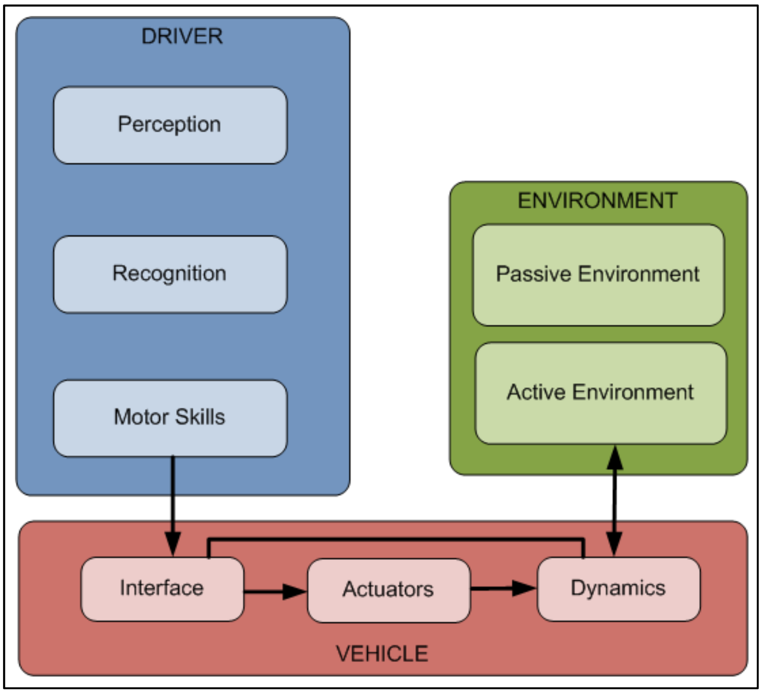

Figure 3.2 Vehicle handling in test maneuvers

[100] ISO - 3888/1 (1999): Test track for a severe lane change manoeuvre

[101] NHTSA (2001): Rollover Resistance

3.2 Classification of Test Maneuvers

Paradigms to classify normal driving conditions and emergency maneuvers can be found in literature.[102] However due to interactions of the previously stated factors, it is clear that no two complex real world maneuver events will yield the same input and output histories. As a consequence, the repeatability and comparability of the experiments will be reduced should the real world maneuver be simulated directly and the simulation be attempted to be validated through utilization of field tests.

In order to validate the simulation model which aims to reproduce the response of a vehicle in a particular intent driven complex real world maneuver, the common engineering sense would demand that the complex maneuver be divided into simpler maneuvers with higher repeatability and comparability characteristics which approximate reality through „pseudo-driving" situations: standardized test maneuvers.

The standardized maneuvers are the maneuvers which clearly exhibit general dynamic characteristics of a vehicle, and are economically feasible, experimentally repeatable and consequentially comparable, but nonetheless in real life nonexistent. They are targeted in simulation studies because of the aforementioned qualities they possess, in order to increase the confidence in a simulation model that it is not invalid, so that it can be used in pursuance of predicting the response of a vehicle to a by no means experimentally repeatable real world maneuver which is turbulent due to the previously mentioned factors.

Note that simulation models seldom have the aim of simulating standardized maneuvers. There would be little meaning in developing a simulation model for a situation, say sine sweep, which is not performed in everyday situations and can easily be experimentally reproduced.

Simulations aim to predict the outcome of driving events that are not experimentally reproducible. The logic behind this expression is that, if an event can be experimentally reproduced (crash tests for occupant safety assessment is not counted as an experiment, since they are aimed to prove and rate the safety of the vehicle for the occupants in the case of different standardized crash scenarios), there is no need to develop a simulation model.

This relationship between the standardized test maneuvers (STMs), simulation models and real world is depicted in Figure 3.3 which demonstrates the so-called validation triangle. Here, the real event is deconstructed and simplified to a standardized test maneuver, the results of which are used in the validity assessment of the simulation model, which aims to predict the outcome of the real event.

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[102] Mitschke (2003): Dynamik der Kraftfahrzeuge

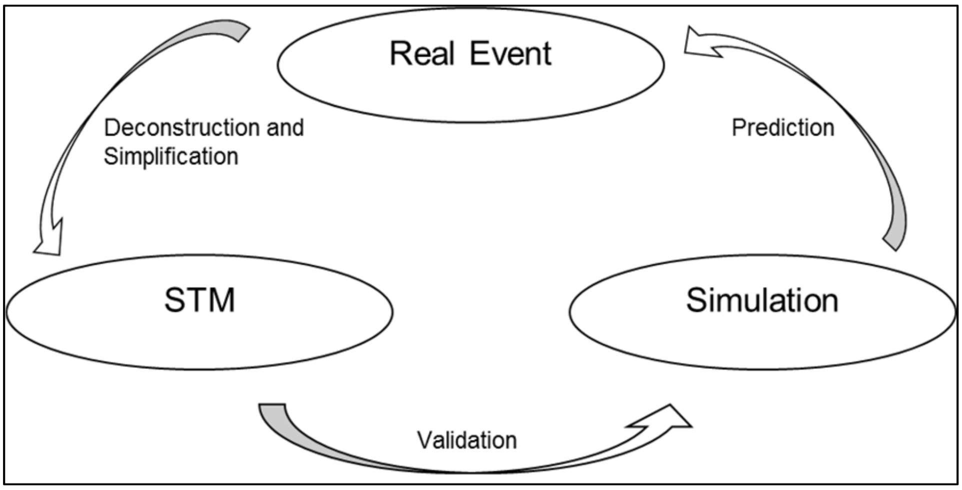

Figure 3.3 The Validation Triangle

The standardized maneuvers can be classified in different ways: According to their relevant analysis domains, input methods, and their scope of application.

A technique to classify the lateral dynamics test maneuvers is using the method with which the input is introduced. This distinction is not defined by if the maneuver is performed with a test driver or a driving robot, but by the definition of the input. If the input is defined independent of any system or environmental elements then the maneuver is classified as an open loop maneuver. Examples to open loop test maneuvers are (but not limited to) steady state cornering maneuver,[103] braking in a turn,[104] power-off reaction in a turn,[105] step response maneuver, single sine input and sine sweep maneuvers[106] and sine with dwell maneuver.[107] The steering input for these maneuvers is predefined and does not change throughout the experiment.

On the other hand, if the trend of the steering input is dependent on any system or environmental elements, such as a predefined value of the lateral acceleration (in the case of a driving robot) or a path to be followed (in the case of a test driver), then the maneuver is classified as a closed loop maneuver. Examples to closed loop test maneuvers are (but not limited to) fish hook turn,[108] yaw acceleration steering reversal

[103] ISO - 4138 (2004): Steady-state circular driving behaviour

[104] ISO - 7975 (2006): Braking in a Turn

[105] ISO - 9816 (2006): Power-off Reaction of a Vehicle in a Turn

[106] ISO - 7401 (2003): Lateral transient response test methods

[107] FMVSS - 126 (2006): Electronic Stability Control Systems

[108] NHTSA (2001): Rollover Resistance

with pause[109] and double lane change maneuver.[110] Note that, the simulation model is run using the experimentally measured input signal, and so is a trace driven system.[111]

Lateral dynamics test maneuvers can also be categorized according to the type of the response and domain in which the resulting data should be analyzed. The response types in this categorization are identified as steady state, transient, periodic and stochastic.

Steady state response is defined as the case in which the variables of interest do not change with time, like the steady state cornering maneuver. In transient response, the systems behavior between the initial equilibrium state and final equilibrium is observed. This can be characterized by introducing a non-periodical and steering input, which ultimately diminishes to zero, to a vehicle which is cruising at constant speed on a straight line or a step response maneuver. Periodic inputs and stochastic inputs are differentiated by the amount of excited frequencies. Most of the time a pseudo-stochastic input, in the form of a trigonometric function which covers the frequency interval in question, is used, since a true stochastic input lowers the repeatability and comparability of test results.

The responses can be analyzed in time and frequency domains. Although one can analyze any measurement in either domain, the maneuvers can nonetheless be classified accordingly, since the considered metrics in any given maneuver is usually in either one the domains. However, some maneuvers are exclusively analyzed in only one domain, the most prominent example being sine sweep maneuver.

The required validation maneuvers can also be divided into two groups from utilization point of view: Fundamental maneuvers and purpose dependent maneuvers.

Fundamental maneuvers are used to determine the main characteristics of the vehicle in time and frequency domain for steady state, transient, periodical and stochastic responses. This kind of maneuvers is mostly rare in every day driving. They exhibit very important dynamical characteristics of the vehicle, and are usually highly reproducible.

On the other hand, purpose dependent maneuvers are the maneuvers, the combination of which can approximate the real maneuver. Although exceptions exist, reproducibility of this maneuver group is relatively low, but they exhibit similar dynamical characteristics to their target real life counterparts. Note that, according to the purpose of the simulation, a fundamental maneuver can also be a purpose dependent maneuver. Table 3.1 provides a summary of the standardized test maneuver classification characteristics. Here, the tick symbol denotes the primary type of the maneuver. An “x” is used for the

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[109] Forkenbrock et. al (2005): NHTSA’s Light Vehicle Handling And ESC Effectiveness Research Program

[110] ISO - 3888/1 (1999): Test track for a severe lane change manoeuvre

[111] Balcı et. al. (1982): Examples of Simulation Model Validation Using Hypothesis Testing

cases where the maneuver cannot be performed by a test driver or a test robot, and a "*" is used to denote that the given option is a secondary choice.

The target maneuvers in lateral dynamics can generally be defined in two groups as critical range and driving range maneuvers. In every day driving, the vehicle can exhibit the full spectrum of its dynamical range (vertical, lateral and longitudinal) in terms of maneuver harshness. For example, in a straight line full braking maneuver, the vehicle will exhibit little lateral dynamics, considerable vertical dynamics (because of the pitch motion) and will reach its longitudinal dynamics limit. However, as explained previously, no two real world events will yield the same results; since there are infinitely many different sets of boundary and initial conditions. Although this does apply to test maneuvers, the set of boundary and initial conditions are rather limited (in order to increase reproducibility and comparability of the results), so is the range of possibly attainable dynamical limits.

Similarly, a simulation model can only include some of these boundary, and initial condition attributes (not the range of values these conditions can possess, but the types of conditions modeled in the simulation). The difference in between is that, once a certain set of boundary and initial condition parameters are defined, one can execute the simulation with any combination of these values. Thus, the simulation model can cover a broader domain than the test maneuvers can.

In a simulation study, in which the aim is to, for example, predict the minimum lap time of a race car on a test circuit, the target maneuvers will be in the critical range. Therefore the purpose dependent maneuvers should be so selected that the effects of lateral tire saturation, rollover limit and full braking/throttle can be observed. However, in a case where the aim of the simulation study is to observe, say, the effects of a particular modification on a vehicle in normal driving range, then the purpose dependent maneuver should also be accordingly selected.

Table 3.1 Classification of selected standard test maneuvers according to input type, domain of analysis, application and response type.

Performed by		Response Type				Application		Domain of Analysis		Input Type		
Steering Robot	Driver	Stochastic	Periodic	Transient	Steady State	Purpose Dependent	Fundamental	Frequency Domain	Time Domain	Closed Loop	Open Loop	
*	✓				✓		✓			✓	✓	Steady State cornering
✓	×			✓		✓			✓		✓	Sine with Dwell
*	✓			✓	✓		✓		✓		✓	Step response
*	✓			✓		✓			✓		✓	Power-off in a turn
*	✓			✓		✓			✓		✓	Braking in a Turn
*	✓		✓				✓		✓		✓	Sinusoidal Input
*	✓		✓				✓		✓		✓	Increasing Amplitude Sinusoidal
×	✓			✓		✓			✓	✓		Double Lane Change
×	✓			✓		✓			✓	✓		Obstacle Avoidance
✓	×			✓		✓			✓	✓		Fishhook
✓	×			✓		✓			✓	✓		Yaw Acceleration Steering Reversal w/ Pause
✓	×			✓		✓			✓	✓		Yaw Acceleration Steering Reversal
*	✓	✓					✓	✓			✓	Pulse Response
*	✓		✓				✓	✓			✓	Continuous Sinusoidal
*	✓	✓					✓	✓			✓	Sine Sweep
×	✓		✓				✓	✓		✓		Slalom

3.3 The V-Model

The V-Model is a project development approach, originally created to structure the development process from global to local entities and then back. Basically it is a top-down and then bottom-up approach. It came into existence as a software development process model for the defense projects of the German Ministry of Defense.[112] It aims reduction of costs over the entire project and system life cycle, minimization of project risks while increasing the final quality of the product through structuring the work flow and practices with well-defined results and responsible roles and enhancing the communication between the stakeholders in order to increase the project transparency, quality of the project management and probability of overall success.[113] The model activities in the model are structured in the shape of the letter “V”, from which the name of the model comes. Coincidentally, “V” is also the initial letter of key words “Verification”, “Validation” and “Vorgehensweise” which means procedure in German.[114]

The left side of the “V”, depicted in Figure 3.4, consists of the planning activities. The hierarchy of these activities decreases from top to bottom as time runs from left to right. The highest order planning activities, which are generally decision of the end configuration of the product, take place at the left tip of the “V”. More detailed and lower order activities position themselves in the lower parts of the left side of the “V”. At each planning stage along with planning, requirements and specifications of the relevant project component are also defined. These requirements and system/module specifications must be defined in such a way that they should be verifiable, ergo falsifiable. Using this approach, the tests and cost of V&V becomes clear at an early stage of the development process, which leads to effective planning and expenditure of the resources.
The bottom of the letter is where implementation takes place. From this point on, the activities start to flow in a bottom up manner, going from lowest configuration item to the highest, along the right side of the ”V”. The processes on the right side of the “V” are associated with verification and validation of the product. At each level, the specification and performance requirements of the components are checked according to the defined tests and criteria.

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[112] IABG (2012): http://www.v-modell.iabg.de/

[113] IABG (2012): http://v-modell.iabg.de/dmdocuments/V-Modell-XT-Gesamt-Englisch- V1.3.pdf

[114] V-Model XT (2012): http://www.v-modell-xt.de/

Once all of the performance requirements and system/module specifications are met by the product (and its subsystem and modules) the final quality of the product is guaranteed. Thus, any element in the performance requirements and system/module specifications must be addressed with at least one appropriate test for validation and verification; and the test performed on the product must be traceable back to at least one performance requirement or specification.

This means that, any testing performed on the product (simulation model) must be serving a purpose (to prove that the simulation model satisfies one or more of the performance requirements or specifications); and any performance requirement or specification is dealt with by at least one testing activity. This can be thought as another case of the Pigeon Hole Principle.[115]

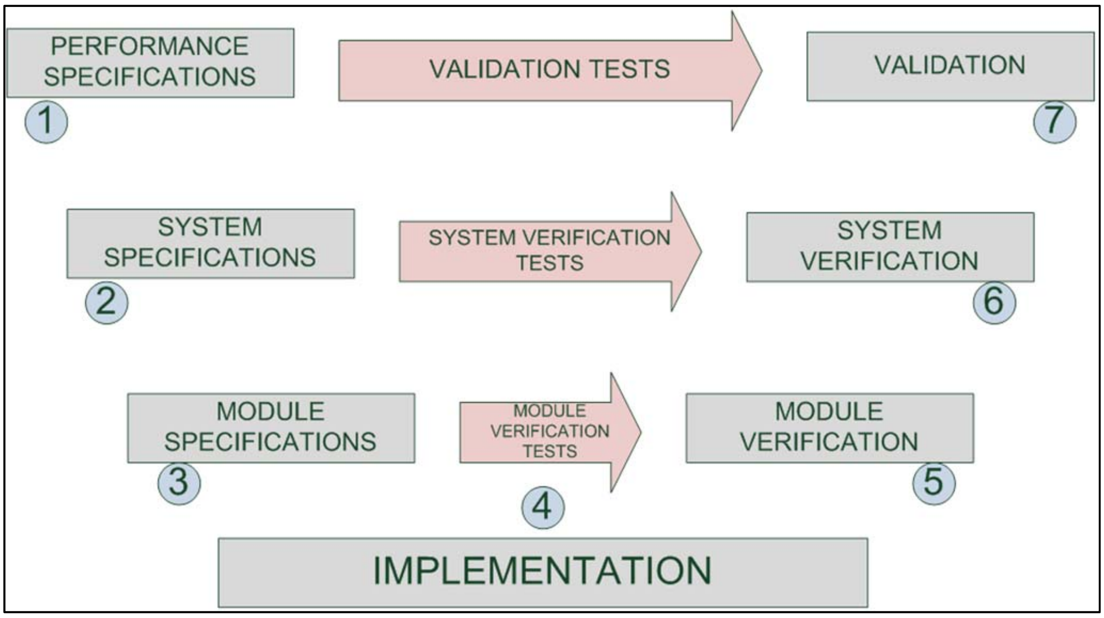

Figure 3.4 The V-Model

Since its introduction there have been modifications, updates and variations on the original V-Model.[116,117,118,119] Dual-V Model and W model are such derivatives of the original approach. In Dual-V Model, the main project plan is represented by the main V, called the architecture V; at each level of which, system components to be processed are represented by their own V's, called entity V's. At each level one or more than one entity V's are branched at ninety degrees in a three dimensional manner. This kind of an operation structure is very suitable for large scale projects with different kinds of system components. It can be concluded that development of a simulation model for a new

[115] Grimaldi (2003): Discrete and Combinatorial Mathematics: An Applied Introduction

[116] IABG (2012): http://www.v-modell.iabg.de/

[117] IABG (2012): http://v-modell.iabg.de/dmdocuments/V-Modell-XT-Gesamt-Englisch-V1.3.pdf

[118] Forsberg et. al. (2005): Visualizing Project Management

[119] Mooz et. al. (2001): A Visual Explanation of Development Methods and Strategies

vehicle would be represented one of these entity V's, whereas the main project (development of a new vehicle) would form the architecture V. On the other hand, in W-Model,[120] a second V, representing the parallel running reviewing, testing and acceptance tests, is placed next to the original V, creating a W form. Many publications can be found in the literature[121,122] about the operation principles and applications of the V-Model and its derivatives. A paradigm that joins the concept of Dual V Model and W Model is yet to be developed, in which both the testing activities run parallel to system development activities in a three dimensional manner conjoining the individual entity W's of subprojects.

3.4 General Validation Methodology According to V-Model

In Figure 3.4, the left side of the "V" is formed by the blocks 1, 2 and 3. Base of the V (block 4) is where implementation process is performed. The right side of the "V" is formed by the execution of verification and validation tests (5, 6, and 7); conditions and methodology of which are determined by the left side of the "V". The nature and content of these tests change from application to application. (Concerning the vehicle dynamics simulation models, the verification of the system and modules (blocks 2, 3, 5, and 6 in Figure 3.4) can be accomplished using analytical solutions to check the findings or checking the module against well known cases,[123] but lies out of the focus of this work which is the validation of vehicle dynamics simulation models.)

Block 1 is where the requirements of the main project are determined, and concerning a vehicle dynamics simulation model, this is the step at which the general validity criteria are to be defined. Here, the aim of the simulation model, as defined by the project manager or the customer, is analyzed. As explained in the previous sections, the real event to be simulated is assessed, and the criteria for a successful simulation are determined.

This is followed by the identification of the required representative standardized test maneuvers to be used in the validation work, that is, the block 7. The benchmark maneuvers to be tested are determined and declared in the simulation requirements document, right at the beginning of the project. Maneuvers should be analyzed according to the input method, domain of interest and excited dynamics to be observed.

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[120] Spillner et. al. (2008): Praxiswissen Softwaretest - Testmanagement

[121] Friedrich et. al. (2008): Das V-Modell XT

[122] Rausch et. al. (2007): Das V-Modell XT. Grundlagen, Methodik und Anwendungen

[123] Allen et. al. (1992): Validation of Vehicle Simulations for Dynamics Stability Analysis

Only after this step can the characteristic metrics of interest be identified and accuracy criteria be defined for each of the determined test cases.

Characteristic metrics of interest are different from test maneuver to test maneuver, and examples are demonstrated in Chapter 4. These metrics are calculated for each experimental measurement and simulation run, and then the statistics of these values are computed. The same metrics are also calculated for the averaged experimental and simulation time histories. Note that, in order to achieve a healthy averaged data set, objective temporal reference coordinates need to be defined (which is also a maneuver dependent process).

The accuracy criteria are defined in two steps: first using the experimental scatter of the data and confidence intervals are defined (95% confidence intervals are used in this work). Then, subjective error allowances are added on top of that, an absolute magnitude or a percentage, depending on the nature of the metric. The practical aspect of choosing between these two options is discussed in the next chapter.

Once the test cases and metrics are identified, the methodology to derive the test metrics, and how the validation conditions and accuracy are defined should be explicitly declared. Such an explicit declaration of how the tests shall be executed, the data be handled, the metric analysis be performed, the assessment be undertaken and the validity criteria be defined, right at the beginning of the project, in accordance with the general spirit of the origins of the V-Model, shall increase transparency and quality assurance of the end product. Final draft of the simulation requirements document should contain the fundamental and purpose dependent test maneuver specifications and execution guidelines for validation work, together with definition of the characteristic metrics and accuracy criteria.

The findings should be honestly analyzed, without leaving any room for model cooking or unintentional self-deception, and the final assessment on the maneuver together with limits and possible error sources should be reported. Note that, in accordance with the famous quote, "…all models are wrong, but some are useful."[124] even if the simulation model fails the defined criteria, such an approach will allow the analyst to identify the "useful" range of the simulation model, in terms of system states (such as lateral acceleration, yaw rate, or input frequency spectrum when vehicle dynamics simulation models are concerned), in which the simulation is "not invalid". Such an aftermath analysis is very useful step in enhancing the simulation and improving the shortcomings in the next release. The explained approach is summarized in Figure 3.5.

[124] Box et. al. (1987): Empirical Model-Building and Response Surfaces

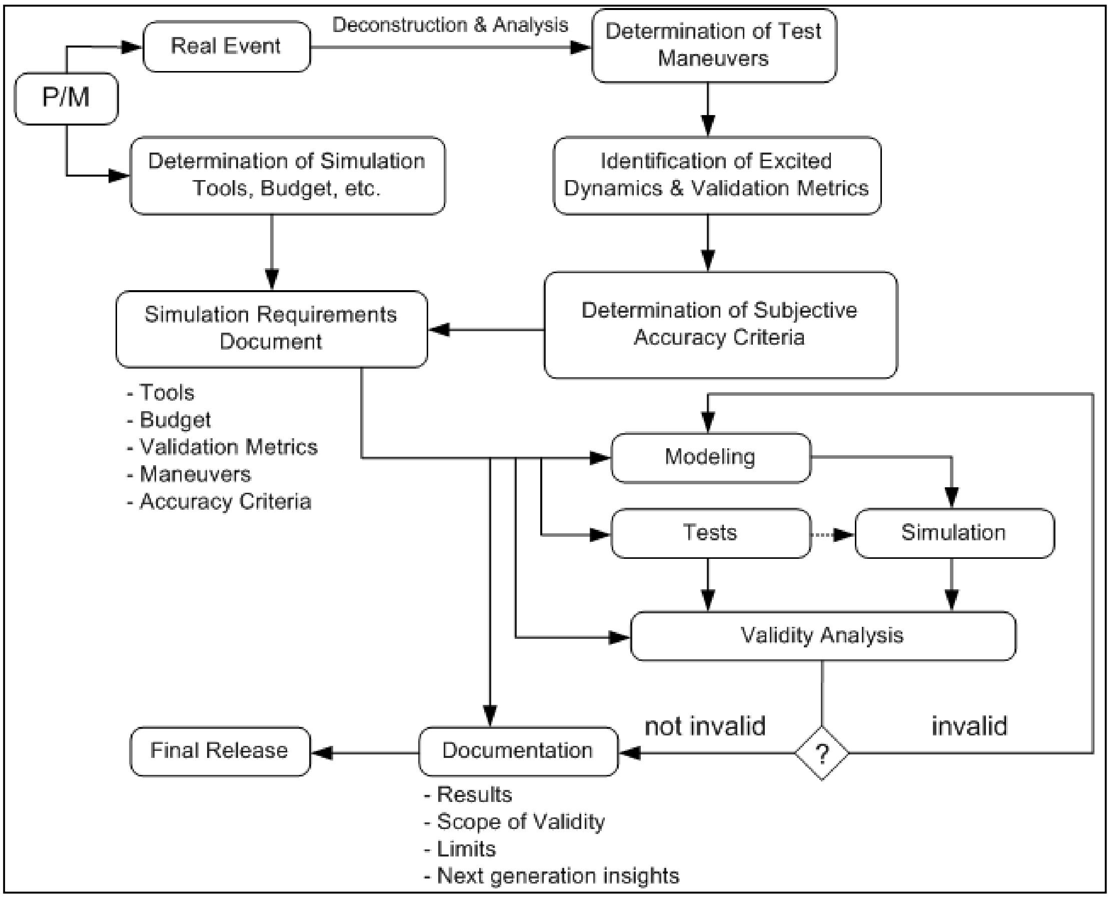

Figure 3.5 Validation Methodology for Vehicle Dynamics Simulation Models (P/M stands for Project Management)

3.5 Conclusion

In this chapter the theoretical aspect of the thesis is tackled. The relationship between the real world events (simulation of which is the actual goal of the simulation model), test maneuvers (which are performed to provide information with which the simulation model can be validated) and the simulation model, the validation triangle (Figure 3.3), is explored. The characteristics of the real world events and the test events are compared, and a classification for standardized test maneuvers is presented. Basic information on V-Model is given and the validation level of the V-Model is analyzed from a vehicle dynamics perspective. Finally, a general methodology to be followed is explained.

The chapter can be concluded as:

- Real world events are intention driven events with infinitely many possible outcomes and boundary/initial conditions and parameter sets, and are not repeatable.

- Test maneuvers are either basic test signals (impulse, step, sine, etc.) applied to vehicle dynamics or simplified versions of common/critical real events, and are repeatable and comparable.
- The aim of a simulation model is to predict the outcome of the real events.
- In order to validate a simulation model, repeatable and comparable real world measurements are needed.
- Test maneuvers, although are not the target of the simulation model, are used to supply measurements with which the simulation model, to be used in the prediction of the real events, can be validated.
- Since the simulation model is aimed to simulate the real events, the test maneuvers to be used in the validation can be selected, analyzed and the validation criteria and analysis methodologies can be defined at the start of the planning stage.
- Each requirement must be translated into a validity criterion, and each of these criteria must be fulfilled for a valid simulation model.
- The explained approach is summarized in Figure 3.5.

4 Case Studies

In this chapter the proposed methodology is further explored and three case studies are presented. A simulation model is built in IPG Carmaker® for the test vehicle, a 2005 Opel Astra H. Methodology used in validation, experimental procedure and simulation model is explained, and three maneuvers are performed and the results are analyzed to assess the validity of the simulation model.

4.1 Methodology

In order to demonstrate the methodology, step response maneuver, sine sweep maneuver and double lane change maneuver are chosen. These maneuvers exhibit a wide variety of dynamical phenomena and classification classes, as seen in Table 4.1, and assure that the demonstration of the validation methodology covers the most important maneuver cases.

Step response maneuver is chosen to test the steady state and transient time response of the maneuver in linear region. According to the aforementioned classification scheme, step response maneuver is a fundamental maneuver, open loop, transient and analyzed in the time domain.

Sine sweep maneuver is used to test the frequency response of the simulation model. Sine sweep maneuver is also a fundamental and open loop, but it is a stochastic maneuver to be analyzed in the frequency domain.

As the third maneuver, a harsher and more real life like maneuver is selected: ISO-3888 double lane change maneuver. Double lane change maneuver is a purpose dependent, closed loop, transient maneuver and is analyzed in the time domain.

Table 4.1 Chosen Test Maneuvers

Maneuver	Type	Input	Response	Analysis
Step	Fundamental	Open Loop	Transient	Time
Sine Sweep	Fundamental	Open Loop	Stochastic	Frequency
Double Lane Change	Purpose Dependent	Closed Loop	Transient	Time

Two of the maneuvers are fundamental, and one is purpose dependent. Again, two of the maneuvers are open loop whereas one is closed loop according to the input. According to the response type, two transient and one stochastic maneuver are chosen. However, one of the transient maneuvers also supplies steady state information and the stochastic maneuver has a periodical nature. Finally, two of the maneuvers are primarily analyzed in the time domain and one of the maneuvers is used for frequency domain analysis.

The chosen maneuvers are analyzed in the subsequent chapters. Validation metrics and validity criteria are defined according to these analyses. Also methods to handle the experimental and simulation data are explained.

4.2 Tools and Research Environment

In this section information on test vehicle, test track and simulation model are presented.

4.2.1 Test Vehicle and Test Track

Test vehicle used in the field tests is an Opel Astra H, currently in FZD car pool, and is used for demonstration purposes, Figure 4.1. Technical specifications of the vehicle are presented in Table 4.2.

Figure 4.1 Opel Astra H used in the tests

Other than the sensors provided by the OEM as standard (see Figure 4.2), the vehicle is equipped with various sensors used in other FZD projects. The external sensors as well as the vehicle sensors through CAN bus gateway, are connected to a dSpace® measurement system. All information gathered in dSpace® can be plotted and saved as time series using the dSpace® workspace application installed on a test laptop computer. In this application the configurations and channels of the sensors are defined and represented as a MATLAB® Simulink® model. The results are saved at the end of each test run and can be opened in MATLAB®.

Table 4.2 Technical specifications of the test vehicle

Property	Specification
Vehicle	Opel Astra H 2.0i 16v Turbo
Engine Displacement	1998 cm^3
Max. Power	125 kW @ 5400 rpm
Max. Torque	250 Nm @ 1950 rpm
Vehicle Mass and Distribution (fl-fr-rl-rr)	1710 kg (490 kg – 485 kg – 370 kg – 366 kg) (fueled, 2 occupants, with experimental equipment)
Yaw Moment of Inertia	1870 $kg.m^2$
Front Suspension	McPherson Strut
Rear Suspension	Twist Beam
Tires	Continental Sport Contact 205/55 R16 91V
Transmission	FWD, Six-speed manual gearbox
Track Width	1488 mm
Wheel Base	2614 mm

Other than the sensors provided by the OEM as standard (see Figure 4.2), the vehicle is equipped with various sensors used in other FZD projects. The external sensors as well as the vehicle sensors through CAN bus gateway, are connected to a dSpace® measurement system. All information gathered in dSpace® can be plotted and saved as time series using the dSpace® workspace application installed on a test laptop computer. In this application the configurations and channels of the sensors are defined and represented as a MATLAB® Simulink® model. The results are saved at the end of each test run and can be opened in MATLAB®.

The data channels used in the present work are the steering wheel angle, yaw velocity, and lateral acceleration channels. Their sensors are the factory installed sensors of the vehicle and are extracted through the CAN bus gateway. Velocity information is obtained using a DatronCorrevit® sensor, located at the rear right bumper of the vehicle.

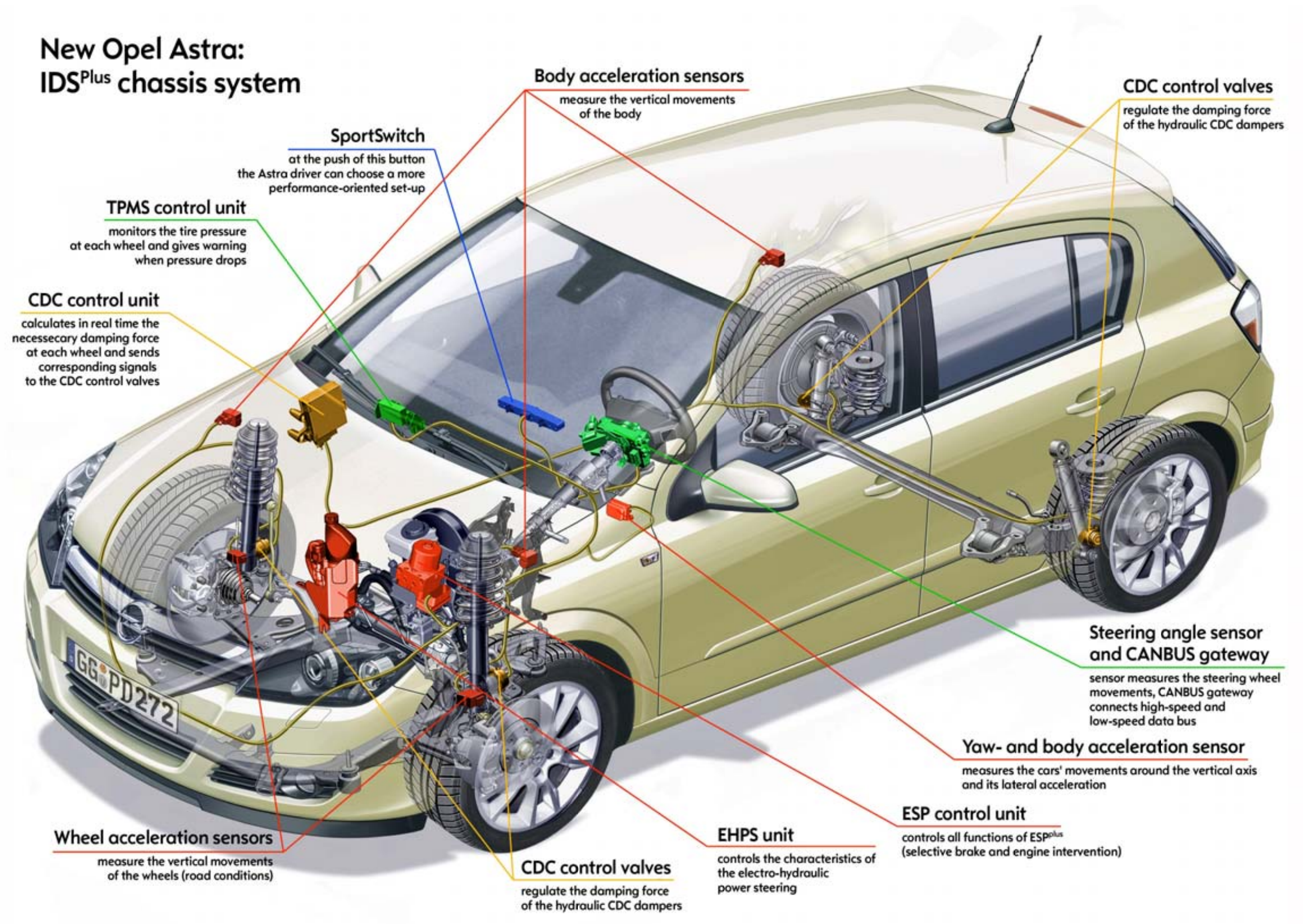

Figure 4.2 Series sensor equipment of the test vehicle. Source: General Motors Chassis Technology (2012): Website - gmeuropearchive.

Figure 4.3 TU Darmstadt Proving Grounds in Griesheim

All test maneuvers are performed in the proving grounds of TU Darmstadt, located in Griesheim (see Figure 4.3). Test track is an out of commission airstrip and its road quality is similar to a typical German highway.

4.2.2 Simulation Model

A simulation to be used in test cases is developed in the simulation software IPG CarMaker®. CarMaker® is a user friendly tool for model development engineers, thanks to its simplified representation of complex systems of vehicles and the capability to change numerous variables and parameters to simulate different conditions and modify signals at will, for example to implement and test a control module.

The simulation model for the test vehicle is based on one of the ready models of the simulation software, an Opel Zafira A. Opel Zafira A is built on General Motors T-Platform (GM3000) and shares many common suspension components with the Opel Astra H, which is built on General Motors Delta Platform (GM3300). In the required subsystems, the parameter values of the Zafira are replaced with those of the Astra. Driveline parameters for example are left untouched, since the maneuvers are performed at constant speed with cruise control engaged, and the longitudinal dynamics have minimum effect on the experiments and therefore are of little concern.

The structural information like the mass distribution and the moments of inertia are derived from the results of the static wheel load measurements. The static wheel load measurements are performed with two occupants (driver and observer) and the measurement equipment. The spring and damper characteristics, and steering system data for the suspension and steering subsystems are taken from previous measurements.[125]

CarMaker® allows the user to implement ADAMs® tire files. The tires used on the test vehicle (Continental Sport Contact 205/55 R16 91V) are modeled using the Pacejka2002 formulation of ADAMs/Tire® and saved as a tire property file ".tir".

Road, track and driver properties are defined separately for each test case. Steering wheel angle and velocity measurements from actual tests are used.

4.3 Step Response Maneuver

In this section the step response maneuver test case is presented. The section includes information on step response of dynamical systems and vehicles, definition of validation metrics, the maneuver specific methodology and analysis results.

4.3.1 Step Response

Step Response of Dynamical Systems

Engineering systems, from aircrafts to buildings, are usually designed to operate not under specific and constant conditions, but in a range of conditions. These operating conditions cover the range of input ranges, system disturbances and environmental conditions in which the system operates.

Although the input range of a system can be limited (amount the steering wheel can turn is mechanically limited in the case of vehicles), unlimited kinds of inputs can be introduced to the system within these limitations by changing the speed, frequency or amplitude of the input signal. The same logic applies to system outputs. The output range of a system can be limited, but the behavior of the system inside these limitations can exhibit infinite diversity. Hence it is impractical to test a system with all possible input signals and output behaviors for which no universal performance metrics can be defined. Common engineering sense is to test the system using simple, easy to generate input functions, which can approximate any input form if the system or at least the response characteristics of the system within the operational range of interest are linear.

Step input is one of the most popular input signals to test transitional response of engineering system. It is a very simple signal and provides very important characteristics of the system.

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[125] Niemz (2006): Reducing Braking Distance by Control of Semi-Active Suspension

The output of a system in response to a step input is called the step response of the system. For linear systems, any input or output signal can be approximated as a series of step signals. That means if the unit step response of a linear system is known, it is mathematically possible to compute the response to any input using the superposition principle.[126]

The ideal step signal is a zero signal until the step time, and reaches its final value by jumping to that value. Thus the system has to deal with this jump and then reach a steady state value defined by the final value of the input signal. In practice it is not always possible to obtain this characteristic jump and in real life application this transition happens in a very short amount of time to approximate the ideal case.

The behavior of the system between the initial conditions and steady state characterizes the transient response of the system, and is an important measure of the system performance. Systems with energy storage and dissipation elements (such as the suspension of a vehicle) cannot respond to the sudden jump of the step input at the same pace and exhibit transient responses.[127] Transient performance of a system to a step input shows how the system will respond to sudden input changes and disturbances. Thus, it is imperative for a simulation model to capture the transitional dynamics of the system, if the sole aim of the simulation model is not to simulate the steady state behavior

Step input and response also provides valuable information on the steady state response of the system and combined with the transient part of the response, step input supplies many important time domain characteristics of a dynamical system single-handedly.

Time Domain Performance Metrics

In order to assess any designed or proposed engineering system, metrics with which the performance can be measured must be specified. Performance metrics concerning the step response of a system deal with time domain performance of the system. These measures of performance determine how fast and how accurately the system reaches the new steady state determined by the amplitude of the introduced step input.

From the point of view of validation of simulation models, the performance metrics are not tools of design by which the system should accordingly be laid out, but criteria to which the simulation model of the system must fulfill. The metrics are measured by experimenting with the actual system, or the forerunner model of the actual system in the case of a proposed vehicle design project. The measured metrics are then utilized to assess the quality of the simulation model. Thus, any design work is performed on the simulation model according to the degree by which the performance criteria are met and

[126] Ercan (2003): Mühendislik Sistemlerinin Modellenmesi ve Dinamiği

[127] Ogata (1997): Modern Control Engineering

not on the system to be simulated. Therefore the performance criteria of the actual system to a step input are not the concern of the validation study; only the experimentally measured performance metrics are.

Commonly used performance metrics, which can be seen in Figure 4.4 are:[128]

- Delay time, t_d
- Rise time, t_r
- Peak time (provided that the system is underdamped), t_p
- Settling time, t_s
- Maximum overshoot ratio (provided that the system is underdamped), M_{os}

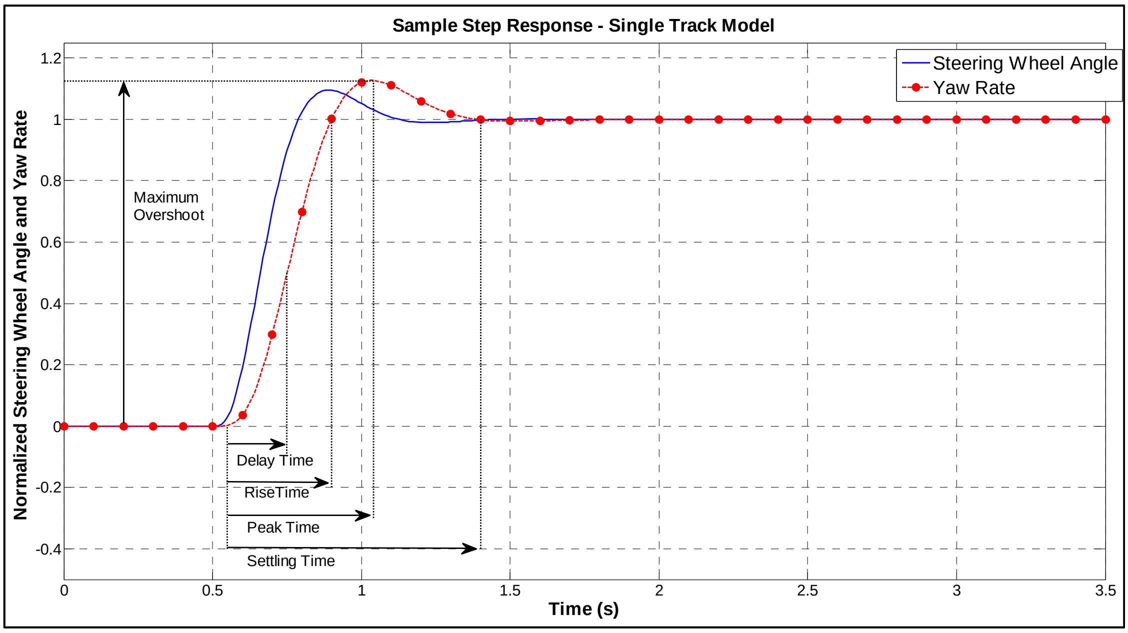

Figure 4.4 Sample Yaw Rate Step Response (Single Track Model Simulation)

The rise time, t_r, is defined as the time passed between the response to reach a certain percentage of the steady state value starting from another predefined percentage of the steady state value. Typical threshold pairs are 5% to 95%, 10% to 90% or 0% to 100%. The threshold pairs are usually chosen according to the characteristics of the system. For example 10% to 90% is typical rise time definition for an overdamped system, e.g. a heavily understeering vehicle.

The delay time, t_d, is the time required for the response to reach the half of the final steady state value for the first time starting from a reference value, usually 0%.

The peak time, t_p, is the time required for the response to reach the first maximum before it is settled. This performance metric is applicable if the step response of the

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[128] Ogata (1997): Modern Control Engineering

system possesses a maximum. Therefore overdamped systems do not have peak time as a performance metric.

The settling time, t_s, is the time required for the response curve to reach and stay within a certain absolute percentage interval of the final steady state value. The width of this interval is usually defined according to the goals of the study, typical values being in the range of 1% to 10%.

The maximum overshoot ratio, M_{os}, is the ratio of the maximum peak value of the response curve and the final steady state value of the response. Similar to peak time, this metric is only applicable if the system is not overdamped and has a maximum value that is different than the final steady state value.

The time-domain specifications just given are quite important since most control systems are time-domain systems; that is, they must exhibit acceptable time responses. (This means that the control system must be modified until the transient response is satisfactory.) Note that if we specify the values of these metrics, then the shape of the response curve is initially determined.

The speed of the transient response and amount of oscillations are the key to factors in assessing the performance. A system that reacts very fast is prone to having more oscillations than desired, and a system that has no oscillations would react sluggishly with respect to a system with lower damping. Thus, the performance metrics usually present an engineering trade off problem. As mentioned before, this problem is not the focus of this study, and these metrics are merely tools to compare the quality of the simulation model with that of the reality.

Step Input Maneuver in Vehicle Dynamics

Step response maneuver for vehicle testing has been defined and standardized by International Organization for Standardization.[129] This document specifies the general requirements and test procedures for testing procedures regarding the transient response of the lateral dynamics of road vehicles. The step response experiments and the sine sweep experiments in the next section are performed with the help of these specifications.

The aim of the test is to measure the transient response characteristics of a vehicle during a transition from straight line driving to steady state cornering. The maneuver consists of the introduction of a sharp change to the steering wheel in straight line constant velocity driving conditions, and holding the final steering wheel angle until the lateral response of the vehicle is stabilized. The amount of acceptable deviations from

[129] ISO - 7401 (2003): Lateral transient response test methods

test speed and starting conditions are defined in the standard as ±2 km/h for longitudinal velocity and ±0.5 °/s for yaw rate.

It is, however, impossible to introduce an ideal step input, since the test driver can turn the steering wheel only within the practical limitations of the reality. Therefore this maneuver is actually a pseudo step input maneuver and the transition between the initial and final values is actually a ramp input with a very steep slope. In order to better approximate the maneuver to a real step input the driver has to change the steering wheel angle in a very short amount of time, so that the ramp part of the input will have a smaller effect and the observed response will mostly be due to the newly attained steering wheel angle. This requirement is defined in terms of the rise time of the steering wheel angle and according to the standard; the rise time between 10% and 90% should not exceed 0.15 s.

The performance metrics defined in the standard (Figure 4.5) are response time, the definition of which is aforementioned rise time, t_r, with threshold defined as 90% of the final steady state value, peak response time, t_p, and maximum overshoot ratio, M_{os}. The time metrics are calculated with respect to a reference time points which is defined as the time value at which the steering angle reaches the 50% of its final value.

In addition to these metrics, steady state gain of the yaw rate with respect to steering wheel angle is also listed among the performance measures of the step response maneuver. All of these metrics can also be found in other sources.[130,131] Additional metrics associated with other measurable and derivable quantities such as lateral acceleration, side slip angle of rear axle, roll angle can also be employed depending on the intended scope of application of the simulation model. In this work, only lateral acceleration and yaw rate metrics are considered.

Note that, in all of the cited sources, the metrics are not measured from initial value of the signals, but a reference time value is defined. This reference time value is the time at which the steering wheel angle reaches the 50% of its final value. However, in order to define a 50% point objectively, the final and the initial values must be clearly identified. When the maneuver is performed without using stops, as would be the case in a real life driving situation, the initial and final steady state value of the steering wheel angle is prone to oscillations. In addition to this drawback, both the initial and final values will not exactly be the same in different experiments. This practically makes it impossible to determine a consistent value for data processing, without the use of a mathematical approach. In the following section a statistical procedure to determine the initial and final values of the input is introduced. Using this procedure, the 50% reference point and the steady state value for the maximum overshoot ratio calculation can be

[130] Nisonger et. al. (1981): Transient Directional Response Test Procedures for Automobiles

[131] Heydinger et. al. (1990): A Methodology for Validating Vehicle Dynamics Simulations

determined independently from the experimental deviations and measurement disturbances.

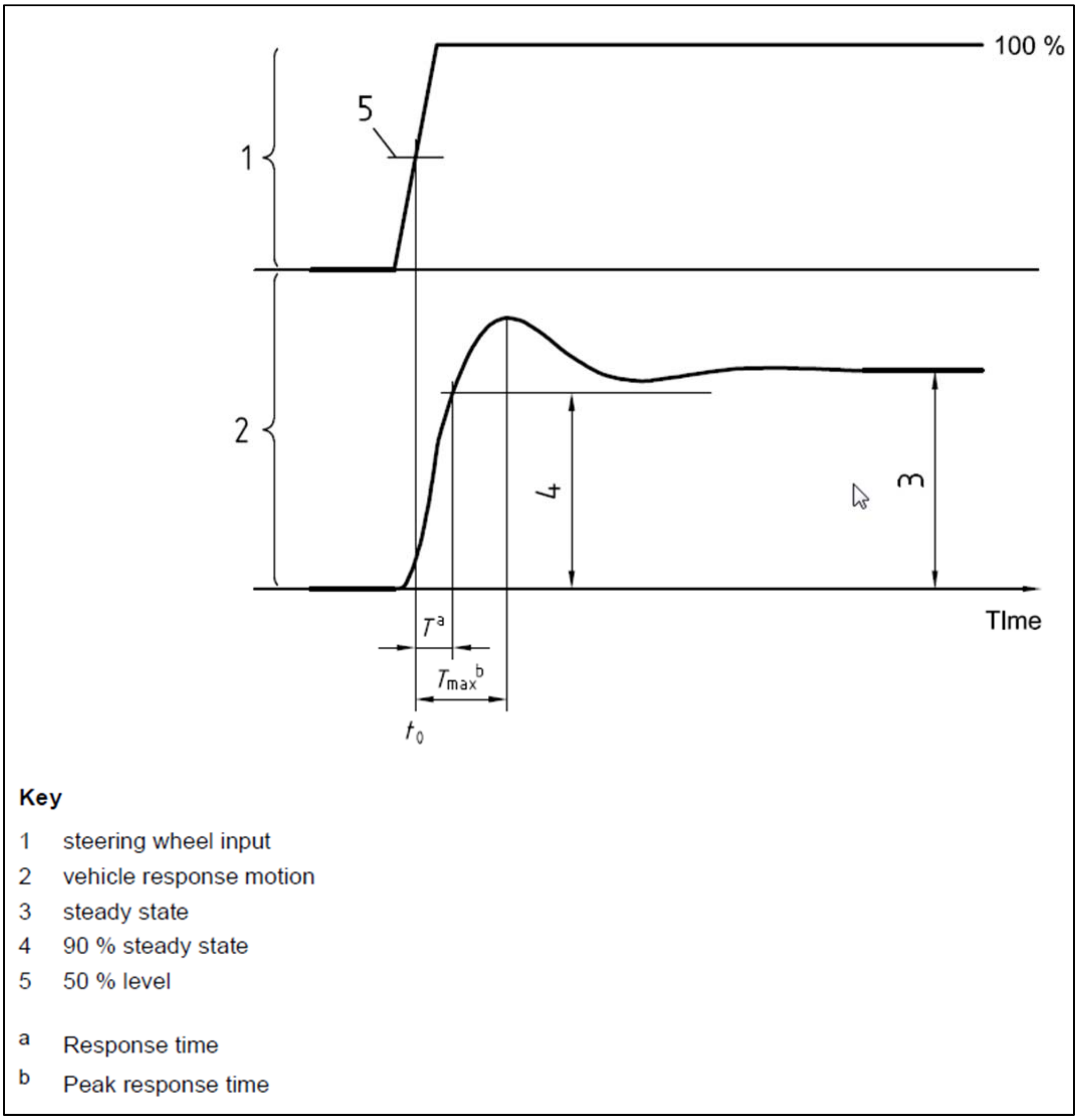

Figure 4.5 Performance metrics as defined in[132]

[132] ISO - 7401 (2003): Lateral transient response test methods

4.3.2 Data Handling and Analysis Methodology

Determining the Reference Time

As explained in the previous section, the validation metrics are all defined with respect to a reference time value. In order to minimize the discrepancies of the value of this reference point between different experiments and enhance the consistency, a statistical method is needed to determine this reference value. In order to develop a solution to this problem, first the steady state signal is analyzed.

A steady state signal has certain properties. Ideally it is a constant signal. However from a practical point of view, decaying or constantly oscillating signals can also be considered as steady state. Moreover any signal will exhibit a certain amount of noise during measurement.

According to the definition in the previous paragraph, an ideal steady state signal (with no oscillating components) has two properties:

- Its mean value is the same in any time interval.
- Its standard deviation is the same and equal to zero in any time interval.

When this constant signal is measured, however, these two properties will not hold anymore. However, for observation intervals of sufficient lengths, the mean values of any two intervals will be similar. These characteristics can be exploited to derive an equation which can aid in defining the regions where the measured noisy signal exhibits steady state like behavior.

If a random interval is taken from the signal, its mean value will be an estimate of the actual mean value of the signal, with a standard error of standard deviation over square root of number of samples in the interval. Assuming a normal distribution, an interval can be defined in which the actual mean value will be located with a given probability, depending on the factor with which the standard error is multiplied with.

The steps of the proposed method are:

1. A test interval that is appropriate to the application at hand is chosen. *This step requires subjective judgement of the analysis engineer.*
2. The test interval is divided into two half intervals.
3. The mean value and the standard deviation of the half intervals are calculated.
4. A coefficient for estimation of confidence band is calculated using Student's t-distribution according to equation 4.1. *This step requires subjective judgement of the analysis engineer.*

$$C = tinv(1 - \alpha, v) \qquad 4.1$$

Where *tinv* is the Student's t inverse cumulative distribution function,[133] v is the degrees of freedom, which is N_1-1, where N_1 is half the number of samples in the chosen interval, and $(1-\alpha)$ is the chosen level of confidence for a one sided distribution case.

5. Upper and lower bounds are calculated according to equation 4.2:

$$U_1 = \mu_1 + C\frac{\sigma_1}{\sqrt{N_1}}, L_1 = \mu_1 - C\frac{\sigma_1}{\sqrt{N_1}} \tag{4.2}$$

Where μ_1 is the mean value of the first half interval, σ_1 is the standard deviation of the first half interval.

6. The mean value of the second half interval is compared to the calculated upper and lower bounds.

$$\begin{aligned}(\mu_2 - U_1) \leq 0 \\ (\mu_2 - L_1) \leq 0\end{aligned} \tag{4.3}$$

Where μ_2 is the mean value of the second interval.

7. Steps (5) and (6) are repeated for the second half interval and if the mean of the first interval stays within the upper and lower bounds of the second half interval as well, then the interval in question is accepted to be a steady state interval.

The whole time history of interest is incrementally tested using this algorithm. A sample result can be seen in Figure 4.6.

Using the described method, the last steady state value (the average value of the last steady state interval) before the step input is commenced; and the first steady state value after the initial rise can be identified. These are assumed to be 0% and 100% steering wheel angle values, and their arithmetic mean value yields the 50% steering wheel angle, and thus corresponding time point with respect to which the metrics are going to be calculated. This reference point will also be used to align the outputs in the following sections.

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[133] Mathworks (2012): http://www.mathworks.com/help/toolbox/stats/tinv.html

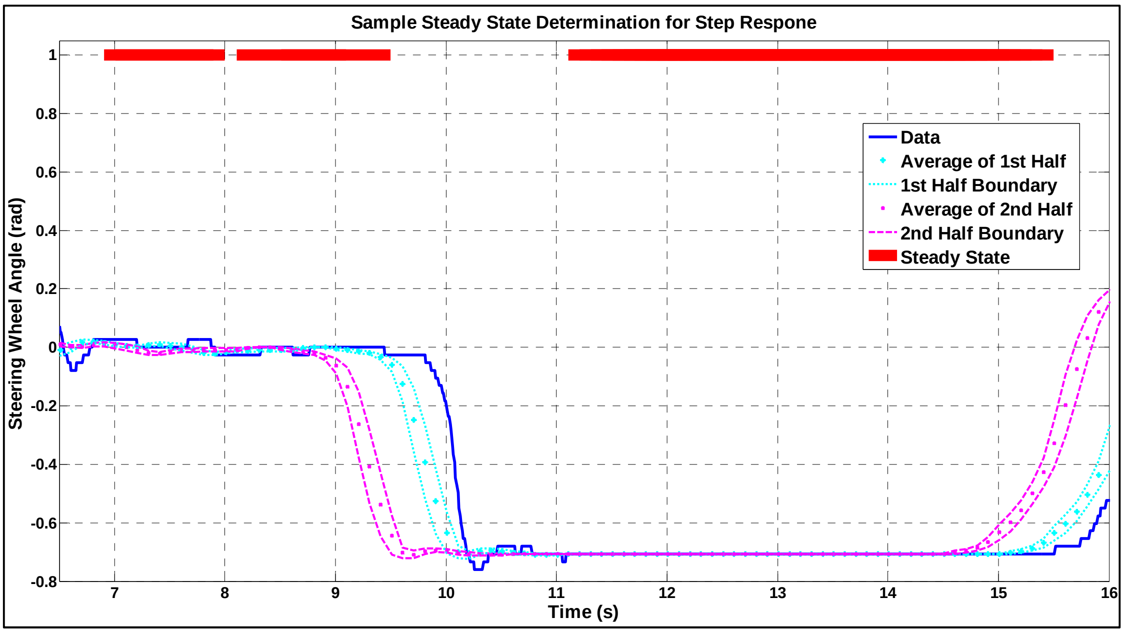

Figure 4.6 Sample steady state determination plot, 1 second test intervals at every 0.1 seconds. Here the red signal denotes the time intervals in which the data is assessed to be at steady state.

Aligning the Output Data

The reference point calculated in the previous section defines the zero time for the performance metrics. These metrics are to be calculated for each of the experiment cases, as well as the corresponding simulations. Additionally, the reference time point can be employed to align the experimental measurements to calculate a mean value and a confidence interval for every sample. The generated mean signal and confidence intervals define an experimental data zone (EDZ).

This validity condition for vehicle dynamics simulation models was first suggested in.[134] 95% Confidence intervals are determined on the quantity in question by utilizing repeated test runs. It was proposed that if the simulated quantity would remain inside the boundaries of the defined uncertainty corridor, the simulation model was valid. It is also a logical consequence that, if the simulation leaves that interval, the model is deemed invalid. Thus, this first approach defines a necessary but not sufficient condition. A simulation which remains inside the experimentally determined 95% confidence interval cannot be deemed valid directly, before the metrics are thoroughly analyzed. Similarly, the simulation should be crossed out, if it fails to satisfy this condition by leaving the experimentally defined data zone.

EDZ is a useful tool when visual comparison of simulation and experimental data is used as a validation tool. It defines an interval for each time step, into which, for example if the confidence interval is chosen to be 95%, the real mean value at that time

[134] Heydinger et. al. (1990): A Methodology for Validating Vehicle Dynamics Simulations

step (the mean value there were infinitely many samples at that time point) will with 95% probability fall into.

If the response of the developed simulation model as well as characteristic metrics are inside the calculated scatter of the experimental data obtained using the corresponding test maneuver through the whole time history, then the conclusion would be that the simulation satisfies both the confidence interval and metric validity criteria. This would theoretically mean that (for a 95% confidence case, since the confidence intervals would define an experimental data zone) simulation response is equally realistic with respect to EDZ and characteristic metrics as calculated in simulation fall into the metric validity windows defined by the spatial and temporal 95% confidence scatter of the characteristic metrics as identified from the experiments.

Metric validity window (MVW) is a visual tool that enables comparing the metrics of the separate measurements with those of the average measurements. The aligning operation establishes a time reference for temporal analysis and allows averaging the signals in interest. However, certain characteristic metrics are prone to changes during the averaging operation, such as the maximum magnitude in step response case.

In general, every measurement will reach its maximum value at a different time (with respect to the reference time used for alignment) and amplitude. When the signals are averaged, the value of the averaged signal will not be the actual average value of measured metrics, but rather an arbitrary maximum value of the averaged measurements, as shown in Figure 4.7. Therefore for certain validation metrics, an averaged diagram tends to provide insufficient information for a healthy analysis.

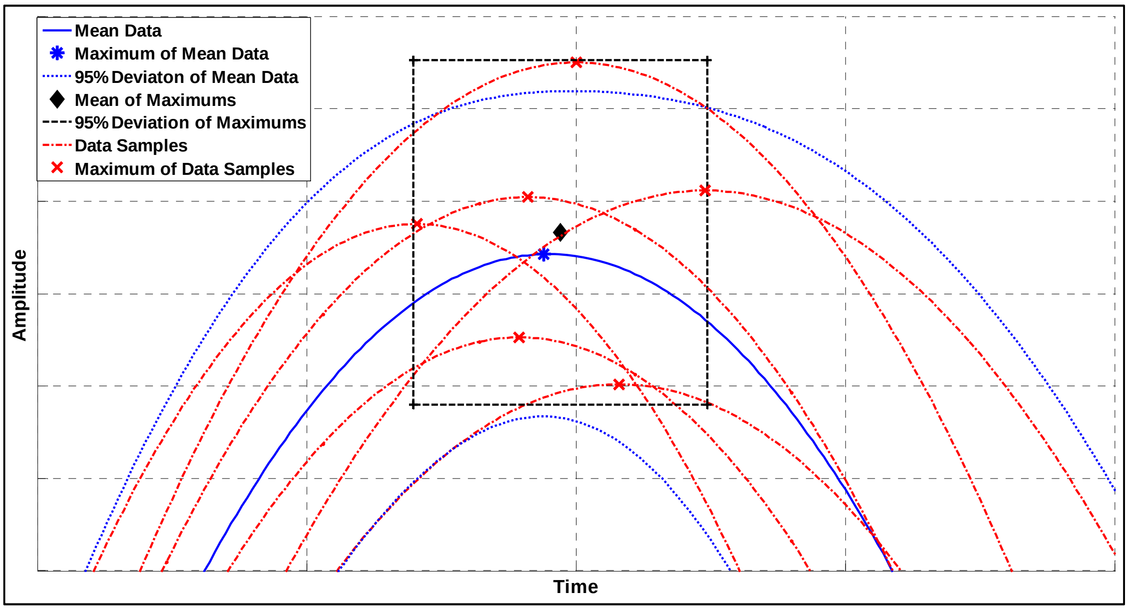

Figure 4.7 Graphical Explanation of MVW Concept: The extremum (and the deviations) obtained by averaging the signals, is not equal to the average (and the deviation) of the extrema of the signals.

Metric validity windows combine temporal and spatial uncertainty of the validation metrics of the separate measurements. Metric validity windows should be superimposed to the generated averaged plots, in order to be able to visually analyze the fit between the validation metrics of the experiments and the simulations.

In this work, the confidence interval for the generation of EDZ and MVW's is selected as 95%, as used previously in the mentioned works. This value is in fact an arbitrarily defined statistical concept, and traditionally in use since it was first time mentioned by Fisher.[135] Unfortunately laws of quantum mechanics state that no matter how perfectly the experiment is controlled and the measurement systems are infinitely accurate, there will always be an arbitrary amount of scatter. Thus, the scatter cannot be prevented and since 100 % interval would mean taking every measurement into account, following the tradition in this case is a reasonable approach.

However, in engineering practice there is always room for error, and as previously stated in Chapter 2, there is no such thing as absolute validity, and thus, EDZ and MVW must both be expanded to introduce a subjective accuracy criteria, which are project dependent (budget, time, feasibility, required quality considerations). These criteria should also be included in the simulation requirement document before the development of the simulation model.

In order to apply the statistical procedure, the experimental data need to be aligned. This effectively means that the time vector of the experimental measurements (and the simulations) needs to be shifted according to the reference time point of every data set. Once this step is accomplished, the mean curve of the simulation runs can be visually compared with the EDZ. Step by step procedure can be seen in Figure 4.8.

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[135] Fisher (1925): Statistical Methods for Research Workers

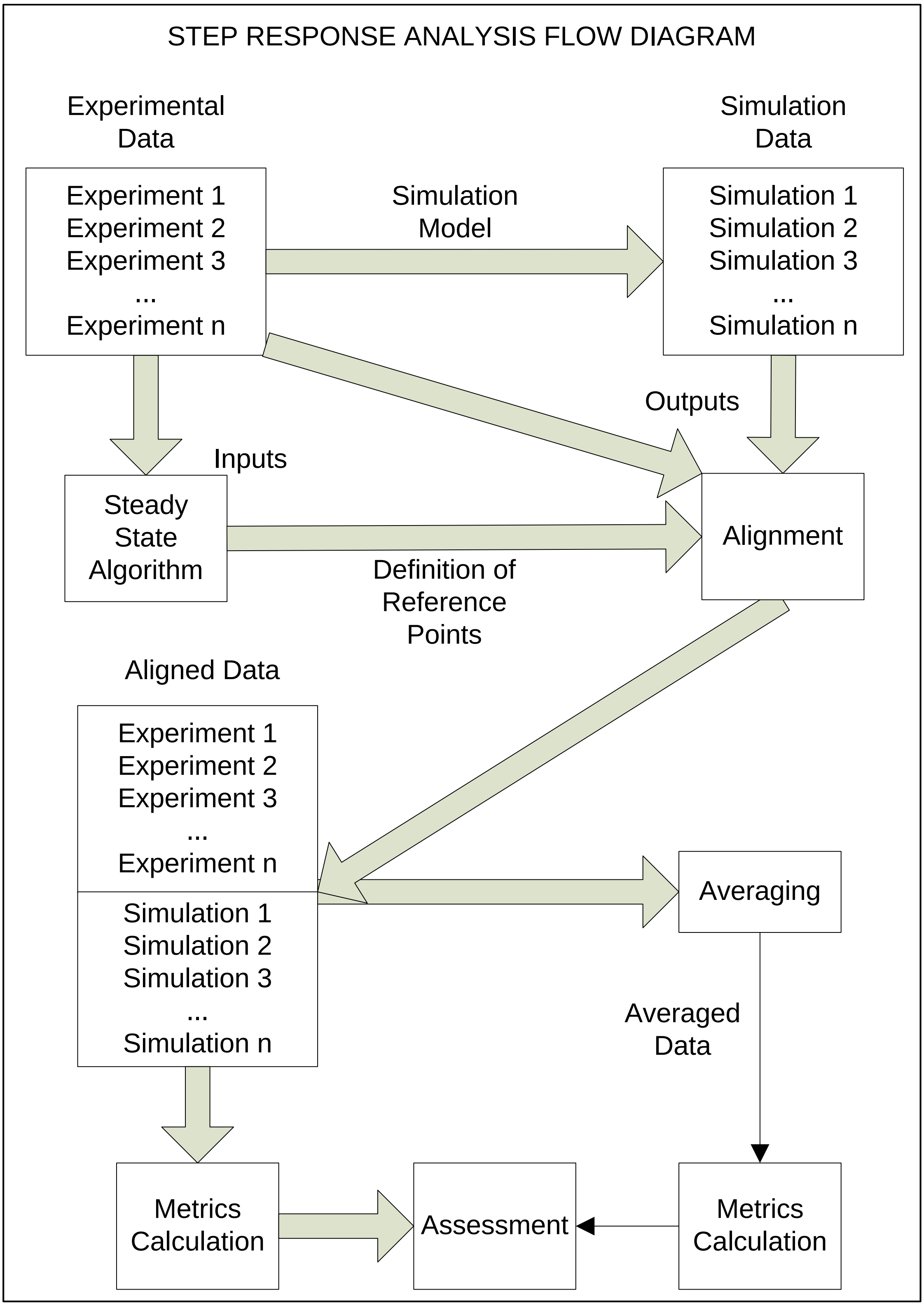

Figure 4.8 Step Response Analysis Methodology

Note that when the aligned experimental steering wheel angle signal is used to excite the simulation model, the alignment step after the simulation can be skipped, as all the simulation response signals will be readily aligned.

Validity Criteria for the Case Study

The metrics for step response maneuver is explained in the previous section. In this section the validity criteria to be imposed on these metrics are presented. The chosen metrics for validity analysis are:

- Steady state gains
- Rise times
- Peak times
- Maximum magnitudes
- Maximum overshoot ratios
- EDZ visual graphics comparison

The validity of the simulation model is assessed by checking the amount of error between the metrics calculated using the experimental measurements and simulation results. Clearly, it cannot be expected that the simulation metrics will be exactly equal to experimental metrics. The amount of acceptable discrepancy should be defined beforehand.

The steady state metrics, steady state lateral acceleration gain and steady state yaw gain for each experimental case, their average and 95% confidence allowance are calculated. The confidence intervals are computed using the methods explained by Oberkampf and Barone.[136] A subjective acceptable error band of 5 % is added to the calculated confidence intervals. The same procedure is followed for simulation results. The average of steady state gains for simulation results should be inside the acceptable deviation from the average of steady state gains of experimental measurements.

The average steering wheel angle signal and average output signals for lateral acceleration and yaw rate are also calculated, for experiment and for simulation. Steady state gains are calculated for all four cases. Note that in this case since there are no other samples to generate a confidence interval, a 5% subjective error allowance is introduced as a validity criterion.

On the other hand, among the transient metrics there are spatial and temporal elements. Rise time, and peak time are the metrics which attempt to assess the transitional temporal performance of the simulation. Much like the steady state gain analysis, these metrics are calculated for each case separately and also for the averaged case. Note that unlike steady state behavior, transitional behavior is hard to reproduce in simulation environment, so an extra error allowance of 0.05 seconds for average of metrics case and 0.1 seconds for metrics of the averaged outputs case are introduced. Percentage allowance in this case is impractical, since the expected values for temporal metrics are already below 0.5 seconds.

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[136] Oberkampf et. al. (2006): Measures of Agreement Between Computation and Experiment

Maximum response and maximum overshoot ratio are the metrics which help compare the damping behavior of the simulation with that of the damping behavior, as observed in the maneuver. The same general principle of analyzing experimental cases and averages separately apply to them as well. Acceptable error in the comparison of averaged signals is taken as 10%. When calculating the validity interval for maximum overshoot ratio, care should be taken to apply this percentage to the amount larger than 1, which is the actual overshoot percentage. However, since the magnitude of this ratio is also generally smaller than 0.5, the validity criteria in this case is chosen to be either the augmented 95 % confidence intervals (95 % confidence intervals plus 10 % of the amount that is higher than 1) or 10 % absolute error.

Moreover, the averaged output signals from experiments with their relative confidence intervals are to be visually inspected. In this visual graphical comparison, the EDZ is plotted on the same diagram with the averaged simulation output. Validity criteria here is that the simulation should stay inside the boundaries except for the transitional zone, where due to high dynamics, very small and actually acceptable errors may deem a simulation invalid if this criterion is applied. A metric validity window for maximum response is to be inserted to this graphic, so that the actual maximum response value can be compared with that of the averaged cases.

4.3.3 Application and Analysis

In this section the application of the previously introduced methodology is demonstrated. The experimental measurements are used to run the simulation. Then the experimental and simulation data are processed according to the flow diagram in Figure 4.8. The validation metrics are calculated and EDZ's and MVW's are generated. Significance of the findings is discussed at the end of the section.

Experimental Data

All experiments are performed at 70 km/h (± 2 km/h) with a final steering wheel angle of 40 degrees (±3 degrees). No steering wheel stops are used. The vehicle is accelerated to the aimed test speed, and cruise control system of the vehicle is engaged. Steering wheel angle is rapidly changed to the required magnitude. This process is highly dependent on the test driver's experience and abilities, but with practice results with adequate quality are obtained.

The quality of the experiments is checked on the site by the tester immediately following the maneuver. In step response maneuver; speed of introduction of the step input, existence and consistency of the initial and final steady state conditions, and the magnitude of the introduced steering wheel angle and the reached lateral acceleration are the important criteria for a successful experimental case. Acceptance criteria for these metrics were supplied to the test crew beforehand.

As previously mentioned, test track allowed only a right hand maneuver, and thus the presented results are only for right hand turn. Obtained experimental measurements are saved as *.mat* files. Parameters that are not included in the *.mat* file are reported in the experiment protocol. A total of 10 experiments are chosen for simulation and validity analysis.

Simulation

Experimental measurements are processed using MATLAB®. A text file with time vector and steering wheel angle magnitudes is generated using Excel® as an intermediate tool. This text file is needed by the simulation package IPG CarMaker® in order to synchronize the steering wheel angle input with the simulation time.

Standard driver settings are used when simulating the step response maneuver. Vehicle speed, gear selection and such experimental parameters are read from the experimental protocol. Simulated road is defined as a sufficiently wide and long paved surface, since the geometrical track characteristics are of no importance.

Simulation model ran on a straight line until the defined maneuver speed is reached, and then the supplied text file is used to manipulate the steering wheel angle. Simulation results are also saved as *.mat* files using CarMaker® for Simulink®.

Data Handling

As a general rule, the signals do not need to be recorded together using a common sampled time vector, although the time values of individual time vectors must be consistent. If the signals also do share a common time vector, the process is simplified, so this practice is recommended.

The experimental measurements in this project do not share a common time vector. That is, steering wheel angle, lateral acceleration and yaw rate all have their own time vectors. In order to be able to align the data and calculate the metrics, all data vector need to be refitted to a common time vector. The zero point of this time vector is defined as the previously explained 50% point of the steering wheel angle. Determination of this reference point is the starting step of the data handling process.

The steering wheel angle data are analyzed using the method explained in Section 4.3.2. and steady state 0% and 100% magnitudes are determined. The 50% point and the relative time value are determined using these two values. The zero of the new time vector is this point. However the data must be modified so that it will be synchronized with the new time vector.

The modification of the steering wheel angle data is performed using linear interpolation. The process is performed between each data point, spaced with 0.01 seconds, and causes negligible error. At the end of this step, a time vector and a steering wheel angle vector are obtained and the magnitude of the steering wheel angle at zero time is the previously calculated 50% point.

The same time vector is utilized to align the lateral acceleration and yaw rate signals. New signals are interpolated and the signals are shifted so that the zero point aligns with the 50% point. Thus, all experimental signals are aligned with respect to 50% point of the steering wheel angle. The same procedure is applied to the simulation data so that the calculated metrics and plotted diagrams are consistent.

Metrics

The analysis of steady state metrics when calculated for each of the experimental and simulation cases are shown in Table 4.3. In order to calculate the 95 % confidence intervals, Student's t-distribution is used.[137] Steady state values are determined running the code through steady state determination algorithm to determine the steady state interval and then averaging.

Table 4.3 Statistical Analysis of Steady State Gains

	Steady State Lateral Acceleration Gain in g/rad	Steady State Yaw Rate Gain in 1/s
Average of Experimental Metrics	0.569	0.282
Upper Bound	0.595	0.291
Lower Bound	0.543	0.273
Average of Simulation Metrics	0.577	0.285
Error Percentage	1.41 %	1.06 %
Absolute Error	0.008	0.003
Result	PASS	PASS

The average of steady state gain of lateral acceleration and yaw rate for each simulation case are within the confidence interval defined by the metric distribution of each experimental case. The amount of error between the average of experimental metrics and those of the simulations for lateral acceleration is 1.41 % and for yaw rate 1.06 %. Thus the simulation satisfies the first steady state validity criterion.

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[137] Oberkampf et. al. (2006): Measures of Agreement Between Computation and Experiment

The steady state lateral acceleration and yaw rate gain of the averaged experimental and simulation data are computed in order to check for the second steady state validity criterion. The findings are presented in Table 4.4. The amount of error between the average experimental signal and the averaged simulation for lateral acceleration is 1.22 % and for yaw rate 1.12 % and both are lower than the acceptable 5 % error allowance. Thus the simulation satisfies the second validity criterion as well.

Table 4.4 Steady State Gains for Averaged Experiment and Simulation

	Steady State Lateral Acceleration Gain in *g*/rad	Steady State Yaw Rate Gain in 1/s
Metrics of Average Experiment	0.572	0.283
Metrics of Average Simulation	0.579	0.286
Error Percentage	1.22 %	1.12 %
Absolute Error	0.007	0.003
Result	PASS	PASS

It is concluded that the simulation model satisfies both of the steady state validity criteria. The next step is to check if the simulation model satisfies the transient validity criteria. Unlike steady state, the temporal metrics come into play in this case. In Table 4.5 statistics of the rise time metric is summarized. The average rise time for simulations is within the defined validity interval for both system outputs. The amount of error for the average of rise time of experiments and simulations for lateral acceleration is 6.64 % and for yaw rate 5.98 %, both within predetermined validity interval.

Table 4.5 Statistical Analysis of Rise Time

	Lateral Acceleration Rise time in s	Yaw Rate Rise Time in s
Average of Experimental Metrics	0.271	0.184
Upper Bound	0.302	0.227
Lower Bound	0.239	0.141
Average of Simulation Metrics	0.289	0.195
Error Percentage	6.64 %	5.98 %
Absolute Error	0.018	0.011
Result	PASS	PASS

As for the rise time of the averaged experimental and simulation outputs, error percentage is relatively lower than the average of separate metrics. It is 2.58 % for rise time of lateral acceleration and 1.6 % for yaw rate and since both metrics are within 0.1 seconds of the rise time of the averaged experimental output, they pass the validity test, as can be seen in Table 4.6.

Table 4.6 Rise Time for Averaged Experiment and Simulation

	Lateral Acceleration Rise time in s	Yaw Rate Rise Time in s
Metrics of Average Experiment	0.271	0.186
Metrics of Average Simulation	0.278	0.189
Error Percentage	2.58 %	1.6 %
Absolute Error	0.007	0.003
Result	PASS	PASS

The second temporal metric, peak time is presented in Table 4.7. Here the error percentage is significantly higher than that of the rise time, but still within acceptable limits. Lateral acceleration error is 14.34 % and yaw rate error is 20.69 %, which is much higher than the rise time error of the yaw rate. On the other hand absolute errors are both within confidence intervals.

Similarly, relative errors of the averaged results are also higher than their counterparts for rise time. Although the error for both metrics is around 18%, absolute errors are within the acceptable error range, as can be seen Table 4.8.

Table 4.7 Statistical Analysis of Peak Time

	Lateral Acceleration Peak Time in s	Yaw Rate Peak Time in s
Average of Experimental Metrics	0.530	0.319
Upper Bound	0.621	0.400
Lower Bound	0.439	0.238
Average of Simulation Metrics	0.606	0.385
Error Percentage	14.34 %	20.69 %
Absolute Error	0.076	0.066
Result	PASS	PASS

Table 4.8 Peak Time for Averaged Experiment and Simulation

	Lateral Acceleration Peak time in s	Yaw Rate Peak Time in s
Metrics of Average Experiment	0.48	0.330
Metrics of Average Simulation	0.57	0.390
Error Percentage	18.75 %	18.18 %
Absolute Error	0.09	0.06
Result	PASS	PASS

Last transient metrics to be checked are the maximum response magnitudes and overshoot ratios. Note that definition of the maximum point is strongly dependent on the filtering process; and in order to guarantee high comparability between the simulation and the experimental results; the same process chain should be employed. In Table 4.9 and Table 4.10, the statistical results are summarized. Here, the simulation's performance fails to deliver values within the confidence intervals for lateral acceleration and yaw rate overshoot ratio, although both metrics are within 10 % range. However the maximum magnitudes are within the acceptable ranges. This discrepancy occurs because of the propagation of the steady state error into the maximum overshoot ratio.

Table 4.9 Statistical Analysis of Maximum Response Magnitude and Overshoot Percentage

	Lateral Acceleration Overshoot Ratio	Lateral Acceleration Maximum in *g*	Yaw Rate Overshoot Ratio	Yaw Rate Maximum in rad/s
Average of Experimental Metrics	1.131	-0.445	1.210	-0.233
Upper Bound	1.192	-0.480	1.277	-0.250
Lower Bound	1.069	-0.410	1.144	-0.215
Average of Simulation Metrics	1.042	-0.420	1.126	-0.230
Error Percentage	7.83 %	5.67 %	5.87 %	1.07%
Absolute Error	0.089	0.025	0.084	0.003
Result	PASS	PASS	PASS	PASS

The simulation model estimates the maximum responses and overshoots ratios of both signals satisfactorily. The error percentages for maximum magnitudes are 5.67 % and 1.07 % for lateral acceleration and yaw rate respectively. The error percentage for overshoot ratios are 7.83 % and 5.87 % for lateral acceleration and yaw rate respectively.

When the overshoot metrics for the averaged outputs are compared better results are observed. All error percentages are below 5 % of the experimental signal. The performance of the simulation model fulfills the overshoot metric criterion as well.

Table 4.10 Maximum Response Magnitudes and Overshoot Percentages for Averaged Experiment and Simulation

	Lateral Acceleration Overshoot Ratio	Lateral Acceleration Maximum in g	Yaw Rate Overshoot Ratio	Yaw Rate Maximum in rad/s
Metrics of Average Experiment	1.092	-0.436	1.171	-0.231
Metrics of Average Simulation	1.053	-0.426	1.127	-0.225
Error Percentage	3.57 %	2.29 %	3.76 %	2.60 %
Absolute Error	0.039	0.01	0.044	0.006
Result	PASS	PASS	PASS	PASS

The final step in the validity analysis of the step response maneuver is the visual graphical comparison of the EDZ with the average simulation output. The aligned steering wheel angle, experimental lateral acceleration and yaw rate signals are averaged. 95 % confidence intervals are calculated for output signals using Student's t-distribution. Simulation results for lateral acceleration and yaw rate are averaged as well. Finally, metric validity window for the overshoot (OS) is plotted. The results are presented in Figure 4.9 and Figure 4.10.

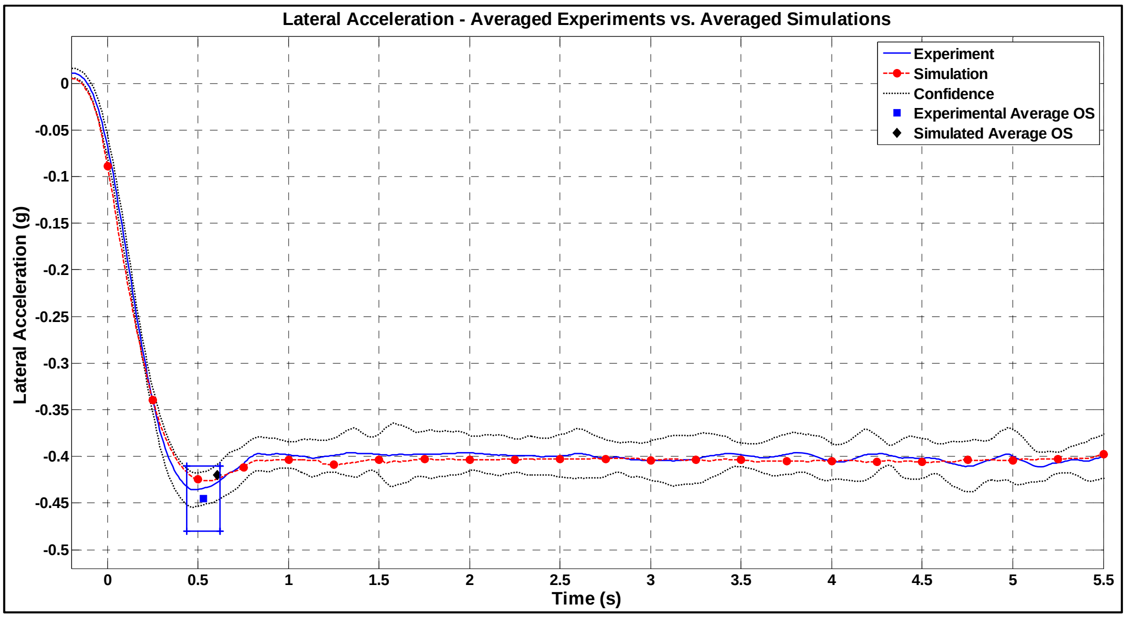

Figure 4.9 Lateral Acceleration EDZ vs. Averaged Simulation

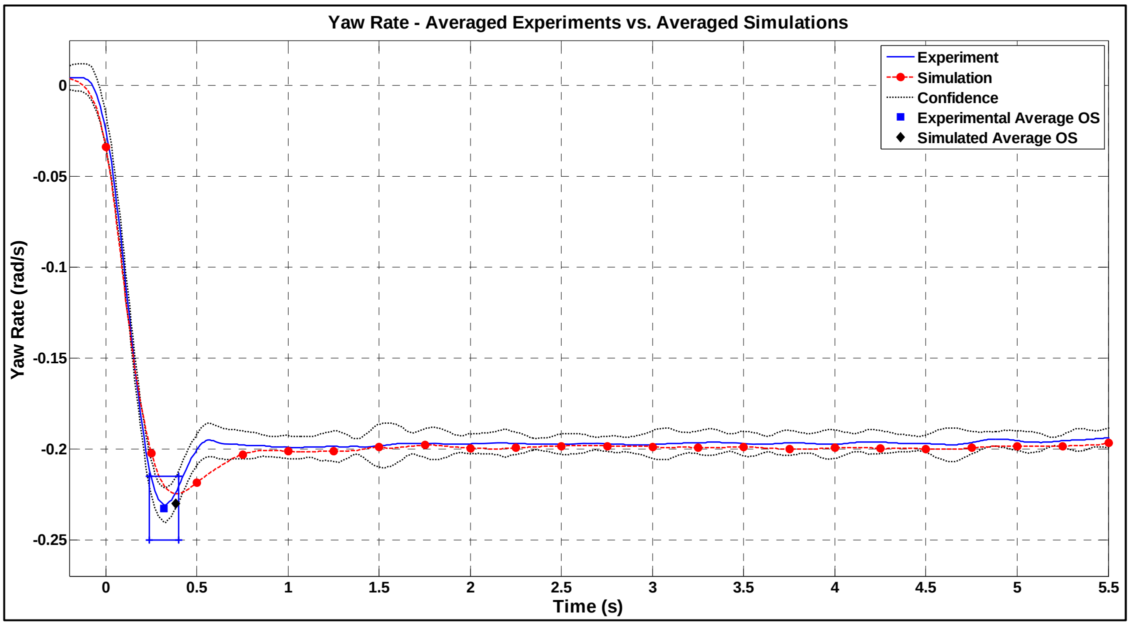

Figure 4.10 Yaw Rate EDZ vs. Averaged Simulation

Discussion of the Results

The calculated metrics all fall within the predefined acceptable error intervals, although temporal metrics exhibit as much as 21% relative error. However, the absolute values of selected temporal metrics are already lower than 0.6 seconds, and absolute error should be considered. Highest amount of absolute temporal error was observed between the average of the peak times of lateral acceleration measurements and simulation values (0.076 seconds).

Averaged simulation results are in accordance with the experimental data zones, staying within the boundaries in the steady state area, and very close in the initial rise area, although not entirely inside the confidence intervals. Simulation model lateral acceleration rises roughly 0.1 seconds earlier than the experimental measurements. This phenomenon can be attributed to inadequate modeling of the lateral relaxation behavior of the tires or unmodeled nonlinearities of the steering system. This problem will be further explored in the double lane change maneuver analysis.

The most notable discrepancy in the EDZ diagrams is the poor yaw rate settling performance of the simulation model. The settling time was not one of the considered temporal metrics in the case study. However the inadequacy of the model is clearly observable in Figure 4.9. This shortcoming is due to the fact that the simulation model has a lower system order (limited to the detail of the used simulation model which is abstract of the dynamics of the real vehicle), and its dominant yaw frequency does not match to that of the real vehicle. The dominant yaw frequency of the vehicle in the test maneuver is higher than the simulation model, and thus the yaw damping behavior of the simulation would have deemed the simulation invalid, had it been chosen among the validity criteria.

4.4 Sine Sweep Maneuver

In this section the sine sweep maneuver test case is presented. The section includes information on frequency response of dynamical systems and vehicles, definition of validation metrics, the maneuver specific methodology and analysis results.

4.4.1 Sine Sweep and Frequency Response

Frequency Response

Frequency response is the variance of the answer of a system depending on the frequency of the input signal. The simplest example is the steady state sine response of a second order system. The output signal attains a certain amplitude and phase value at steady state. A vehicle is a higher order system, but the same basic principles apply to some degree.

Although any signal can be analyzed in the frequency domain, sine sweep and impulse inputs which excite a spectrum of system frequencies in order to explore the frequency response of vehicles. Time measurements from the system are transformed to frequency domain using Fourier Transformation.

Fourier Transformation and its application to discrete time series are well documented[138,139] and is based on representing the signals by infinite number of sine and cosine waves with different amplitude and frequency. As a reflection of this consideration a signal can be created by superposing a series of sine and cosine waves with known amplitude and frequency. System response gains and phase angles are calculated as a function of frequency. Such an analysis reveals the response characteristics of systems, vehicles in this case, such as the most or least responsive frequencies, or system lag at different frequencies.

Sine Sweep Maneuver

Sine-sweep maneuver is defined as stochastic in the standards,[140] due to its matching frequency response, although it is a deterministic maneuver. In reality the maneuver is pseudo-stochastic,[141] but can replace a truly stochastic signal because of its similar properties in frequency domain. The resulting response signals are represented as oscillations in the time domain, but they contain valuable frequency information in the frequency domain.

The primary object of this test is to determine the transient behavior of a vehicle. Characteristic values and functions in the time and frequency domains are considered necessary for characterizing vehicle transient response. If the simulation model is subjected to the same steering wheel inputs and the simulation outputs are also transformed to frequency coordinates, the frequency responses of the experiment and simulation can be compared. Such a comparison reveals valuable information on the shortcomings, strengths and limits of the simulation model. Such methods are also very helpful in identifying the subsystem weaknesses in multibody and FEM models.[142]

Sine sweep maneuver is performed by introducing a slowly increasing frequency steering wheel input. Starting frequency is 0.2 Hz typically. Highest frequency depends on the test driver’s capabilities, but usually lies between 2 to 3 Hz. Details of the sine sweep maneuver are standardized as an ISO document.[140] The sweep amplitude for steering wheel angle is determined by driving a steady state curve with a selected lateral acceleration, under the linear response limit. The maneuver is performed at constant velocity, on dry asphalt and with little or no wind. The standard calls for a measurement of at least 12 minutes, but allows separate measurements to be taken, if the test track is not long enough for such data capture.

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[138] Cooley et. al. (1965): An Algorithm for the Machine Calculation of Complex Fourier Series

[139] Ingle et. al. (2011): Digital Signal Processing Using Matlab

[140] ISO - 7401 (2003): Lateral transient response test methods

[141] Nisonger et. al. (1981): Transient Directional Response Test Procedures for Automobiles

[142] Cassara et. al. (2004): A Multi-Level Approach for the Validation of a Tractor-Semitrailer Ride and Handling Model

4.4.2 Data Handling and Analysis Methodology

After performing the sine sweep maneuver with pre-defined specifications, the time histories of the vehicle responses are captured. These time history signals need to be processed in order to perform a validation analysis in frequency domain. A methodology proposal is demonstrated that can be used to prepare input vector for simulation model, perform frequency analysis, and process the experimental and simulation data for the validation analysis.

The measurements should be subjected to a preliminary analysis to make sure that adequate frequency content is captured in the measurements. Standard can be referred for the details of these analyses.[143]

Filtering is also a concern and should be performed before the simulations and the analysis. The test system used in this work records the measurements of the ESC system of the vehicle, and the signals are already filtered. On the other hand if this was not the case, analog, followed by discretization, followed by digital filtering is the correct course of action. The requirements and guidelines for filtering can be found in the ISO-7401 standard.[143]

At 80 km/h, a total length of approximately 16 km is required to capture an uninterrupted 12 minutes of measurements. Options include performing the maneuver with a test driver or with a steering robot and implementing one long sine sweep or continuous reversed back to back sine sweeps. If a test driver is used, twelve minutes of constant dynamical steering will fatigue the driver, especially when performing the higher frequency parts and will lead to poor input quality. Also, 12 minutes of uncut measurements will require comparatively high computational resources, and such an experiment calls for a straight test track of at least 16 km. The practical course of action is to perform maneuvers in portions. This way, any bad quality measurement can be eliminated without the need to repeat all 12 minutes of experiment, and a relatively shorter test track will be adequate.

However, separately calculated frequency contents need to be averaged for analysis; and in order to accomplish this, the frequency resolution of the datasets need to be the same. This can be accomplished by using the same experimental recording lengths for every experiment, which is in general not the case. Thus there is a need to preprocess the steering wheel angle measurements before they are sent to the simulation model. Steering wheel angle measurements should be cut to their effective lengths and be made sure that they are of the same length. A practical solution is to take the longest measurement, and zero pad the rest of the measurements to that size. There is no need for alignment, since it does not matter where the actual data is located in the time frame,

[143] ISO – 7401 (2003): Lateral transient response test methods

as long as the same procedure is applied to corresponding output measurements. A suggestion to determine the effective lengths is using the first and last zero crossings before the first and after the last maximum of the maneuver.[144]

Once all data sets are dimensionally equalized, that is, the sampling rate and length of all of the data sets, the inputs and the outputs, are the same; the simulations can be performed using the steering wheel angle measurements. The simulation outputs shall also be subjected to same process for the same reasons.

Following this step, the signals are transformed to frequency domain using Fourier Transformation. In this work, MATLAB® is used to perform the discrete Fourier Transformation. In-built Fast Fourier algorithm *fft.m* is used for this purpose.

Coherence functions are also needed to be built, in order to determine the range within which the output signals are directly caused by the input signal. Lower coherence values represent the noise or a strong non-linearity in the system response and/or the measurement system. The coherence function is a real function between zero and one, which gives a measure of correlation between an input and output signal at each frequency. In other words it determines the cause-effect relationship between the input and output of a system. The coherence function is used to determine how "good" two signals "matches", and the "random error".[145] A poor coherence is a cause of non-linearity, not-correlating noise of two signals, the effect of other signals to the output signal that are not bases on the input signal, and the leakage effects, caused by poor frequency resolution.[146] Additionally, the coherence function ranges of the experiment and the simulations can be compared with each other, in order to ensure that the frequency behavior of the model is the same with real vehicle. Equation used for calculation of coherence function is provided in equation 4.4. Here G_{xx}, G_{yy} are auto spectral densities of input and output functions respectively, and G_{xy} is the cross spectral density between input and output.

$$C_{xy}(\omega) = \frac{\left|G_{xy}\right|^2}{G_{xx} \cdot G_{yy}} \qquad 4.4$$

Calculated frequency functions are used to compute the complex transfer functions between lateral acceleration and yaw rate, and the steering wheel angle according to equation 4.5. This operation is performed for each data set separately. Then, in order to lower the measurement noise, the real and imaginary parts of these sets are averaged (and their standard deviations are calculated for the next step) to obtain the real and

[144] Alaloğlu (2011): Simulation of Opel Astra H with CarMaker and Validation of the Model Using Sine Sweep Maneuver

[145] Lessard (2006): Signal Processing of Random Physiological Signals

[146] FZD (2010): Tutorial Digitale Signalverarbeitung

imaginary parts of the average complex frequency response functions. The mean amplitude and phase angle can be calculated using equations 4.6 and 4.7.

$$F_{a_y,s}(\omega) = F_{a_y}(\omega)/F_s(\omega)\ ,\ F_{\dot{\varphi},s}(\omega) = F_{\dot{\varphi}}(\omega)/F_s(\omega) \qquad 4.5$$

$$\left|\bar{F}_{a_y,s}\right| = \left(\left(\overline{Re}_{a_y,s}\right)^2 + \left(\overline{Im}_{a_y,s}\right)^2\right)^{1/2}$$
$$\left|\bar{F}_{\dot{\varphi},s}\right| = \left((\overline{Re}_{\dot{\varphi},s})^2 + (\overline{Im}_{\dot{\varphi},s})^2\right)^{1/2} \qquad 4.6$$

$$\left|\bar{\Phi}_{a_y,s}\right| = arctan\left(\overline{Im}_{a_y,s}/\overline{Re}_{a_y,s}\right)$$
$$\left|\bar{\Phi}_{\dot{\varphi},s}\right| = arctan\left(\overline{Im}_{\dot{\varphi},s}/\overline{Re}_{\dot{\varphi},s}\right) \qquad 4.7$$

The standard deviations of the real and imaginary parts are used to obtain confidence intervals. Confidence intervals of the amplitude and phase angles of the transfer functions can be calculated using equations 4.8 and 4.9. Note that, the equations are given for only one standard deviation width. The standard deviation components in these equations can be replaced with the confidence intervals calculated using equation 4.2 with desired amount of uncertainty percentage, and extended with acceptable amount of discrepancy.

$$\sigma\left|\bar{F}_{a_y,s}\right| = \left(\left(\sigma(\overline{Re}_{a_y,s})\right)^2 + \left(\sigma(\overline{Im}_{a_y,s})\right)^2\right)^{1/2}$$
$$\sigma\left|\bar{F}_{\dot{\varphi},s}\right| = \left(\left(\sigma(\overline{Re}_{\dot{\varphi},s})\right)^2 + \left(\sigma(\overline{Im}_{\dot{\varphi},s})\right)^2\right)^{1/2} \qquad 4.8$$

$$\sigma\left|\bar{\Phi}_{a_y,s}\right| = arcsin\left(\sigma\left|\bar{F}_{a_y,s}\right| / \left|\bar{F}_{a_y,s}\right|\right)$$
$$\sigma\left|\bar{\Phi}_{\dot{\varphi},s}\right| = arcsin\left(\sigma\left|\bar{F}_{\dot{\varphi},s}\right| / \left|\bar{F}_{\dot{\varphi},s}\right|\right) \qquad 4.9$$

Note that the phase angle calculations are valid only for small angles. A summary of the methodology can be seen in Figure 4.11.

Validity Criteria for the Case Study

Typical performance metrics in frequency domain are the peak response frequency, peak amplitude ratio (ratio of the peak gain in frequency domain and the steady state gain) if there is a peak, bandwidth (the frequency at which the frequency gain drops 3 dB below steady state gain), the frequency at which the phase angle reaches 90 degrees.[147]

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[147] Heydinger et. al. (1990): A Methodology for Validating Vehicle Dynamics Simulations

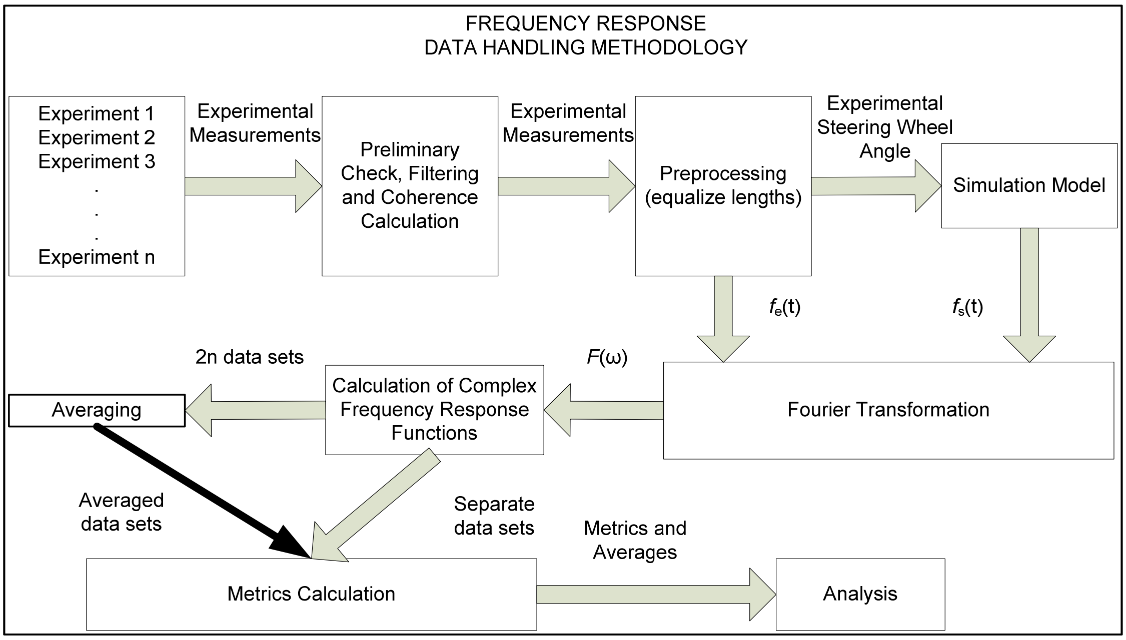

Figure 4.11 Frequency Response Data Handling Methodology

Additionally, any selected reference point can be defined as a validation metric, say the frequency at which the phase reaches 45 degrees; or any characteristic point, say if the phase angle or the frequency response has an extremum. Note that, curve fitting may be necessary for such definitions, and in that case, the same curve fitting technique should be applied to all of the cases.

For the present work, only the visual graphical comparisons of the averaged response gain and phase diagrams are considered. The simulation average shall stay inside the boundaries defined by the 95% confidence interval of corresponding validation variable computed using Student's t-distribution, plus a subjective divergence allowance for the entire steering angle input frequency interval. This allowance for lateral acceleration and yaw rate gains is ±%10 of the gain magnitude at 1 Hz. The allowance for phase curves is taken as $\pm 15^{o}$. An alternative approach could have been deriving the group delay and imposing an acceptable error band, such as 10%.

4.4.3 Application and Analysis

Experimental Data

The steering wheel angle required to obtain 4 m/s^2 lateral acceleration at 80 km/h is measured as 35^{o}. The test track limited the performable recording length approximately to 40 seconds. A total of 24 experimental runs of 30 seconds active steering time are performed, totaling to 12 minutes of measurement. Tests are conducted at 80 km/h, with a logarithmically increasing sine sweep signal with lowest frequency 0.2 Hz and highest frequency 2 Hz. 0.2 Hz lower limit is imposed by the width of the test track. At lower frequencies vehicle's motion in lateral direction is considerable. 2 Hz limit is mostly imposed by the capabilities of the test driver. A sound file prepared in MATLAB® is used to guide the driver throughout the maneuver. No steering stops are used because of their negative effect on the periodicity of the input signal. Cruise control system of the vehicle is engaged during the maneuver to ensure constant velocity.

Simulation

Experimental measurements are processed using MATLAB® and Excel® and a text file with time vector and steering wheel angle magnitudes is generated for each experiment. The simulation package IPG CarMaker® uses this text file in order to synchronize the steering wheel angle input with the simulation time.

Standard driver settings are used when simulating the sine sweep maneuver. Experimental parameters are read from the experimental protocol. The geometry of the test track is not modeled and the simulation road is defined as a sufficiently wide and long paved surface.

Simulation model ran on a straight line until the defined maneuver speed is reached, and then the supplied text file is used to manipulate the steering wheel angle. Simulation results are also saved as *.mat* files using CarMaker® for Simulink®.

Data Handling

Data handling is performed according to the methodology explained in section 4.4.2. As previously explained, the measured information is already filtered by the ESC unit of the vehicle.

Data handling process starts with the data cutting operation. The starting point of the cutting process is placed at the last zero crossing before the first maximum and the end point is the last zero crossing after the last zero crossing. Although the used sound signal lasts exactly 30 seconds, when the effective lengths of all 24 test runs are examined, it is concluded that the last zero crossing varies from experiment to experiment. A fixed length that is longer than 30 seconds is therefore needed. In order to prevent noise from inactive time, when the steering wheel angle is zero before and after the active steering part, all data vectors are completed to 32 seconds with adding two zero vectors to the beginning and at the end of the cut part of the data, so that all data vectors are the same length. The temporal positioning of the signals do not matter, since the analysis take place in frequency domain.

At this point, in order to minimize the effect of any possible frequency jump between the zero padding and the actual steering wheel measurement, the cut data is then windowed with a composite 50% overlapping Hann window. The principle window width is so chosen that the window reaches its maximum before the first zero crossing and starts to attenuate after the last zero crossing, as shown in Figure 4.12.

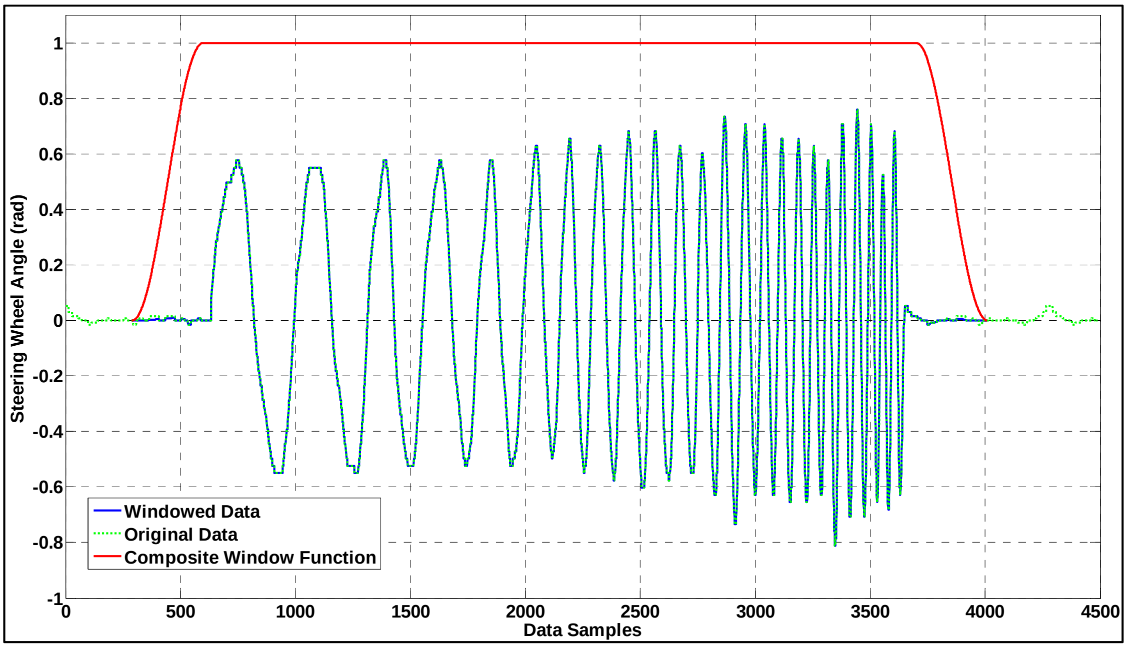

Figure 4.12 Sample Composite Hann Window

The windowed data is then transformed from time to frequency domain with fast Fourier transformation function of MATLAB® (*fft.m*). After transformation, the output data vector is divided to input data vector in frequency domain, in order to determine the complex transfer functions between the lateral acceleration and yaw rate, and the steering wheel angle. The magnitudes of the elements of the complex transfer function vector define the amplitude of the response (gain) and the inverse tangent of the ratio of the imaginary part to real part of the elements of the complex transfer function provide the phase angle information.

The coherence functions are built to ensure that the signals originate from the input signal and to determine the frequency range of interest. The signals are accepted as coherent in the frequency range, where the coherence level is higher than 0.9. Coherence function is calculated using *mscohere.m* function of MATLAB®. Examining the coherence functions of the measured input and output signals the frequencies are determined, up to the signals are coherent. In Figure 4.13 and Figure 4.14 sample coherence functions of lateral acceleration and yaw rate for sine sweep maneuver are presented. Here, the lateral acceleration signal is coherent with the steering wheel angle up to 1.46 Hz and the yaw velocity is coherent up to 1.67 Hz, with coherence level higher than 0.9 up until these frequencies.

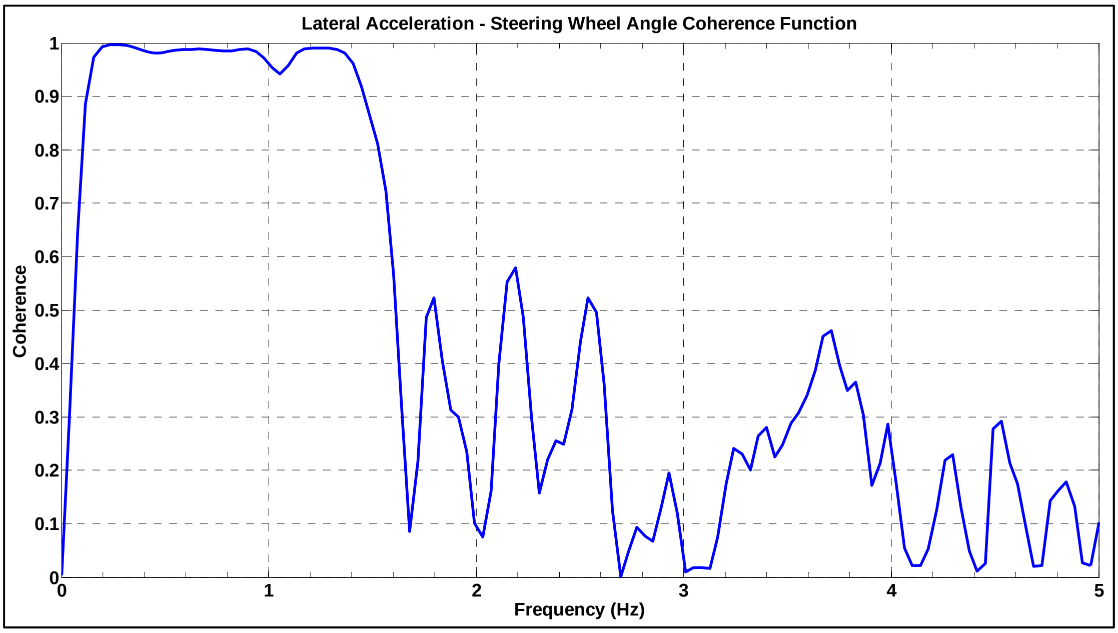

Figure 4.13 Sample Coherence Function of the Lateral Acceleration

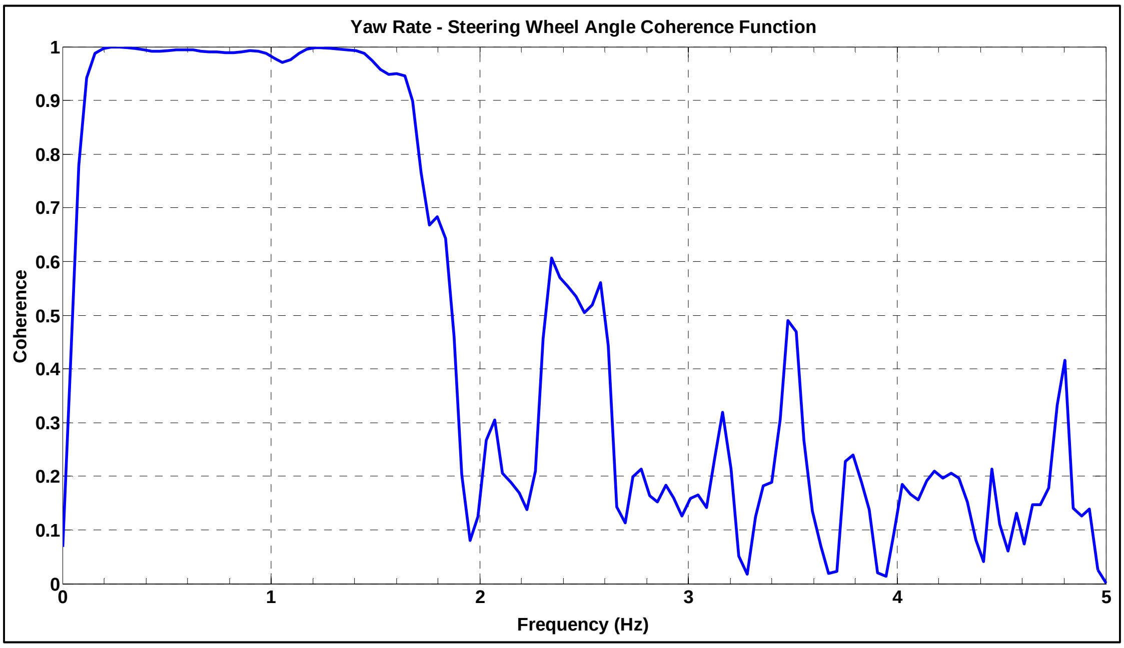

Figure 4.14 Sample Coherence Function of the Yaw Rate

Metrics

At this stage there are 24 data sets for lateral acceleration and yaw rate response gains, and phase angles as a function of frequency, both for experiments and simulation, making a total of 192 data sets. Of these 192 data sets, half are experimental measurements. These measurements are averaged (hence, reduced to 4 data sets) and 95% confidence intervals are calculated using Student's t-distribution. Then, in order to define the EDZ, 10% of the magnitudes of the response gains at 1 Hz are added to the response gain and $\pm 15^{o}$ is added to the phase angle uncertainty bands.

Simulation data sets are only averaged. Experimental averaged response gains and phase angles are plotted onto the same diagram with their simulation counterparts, along with the confidence intervals. Only the active steering frequencies are included in the analysis. The magnitudes of the response gains are presented in Figure 4.15 and Figure 4.16. The phase angles are presented in Figure 4.17 and Figure 4.18.

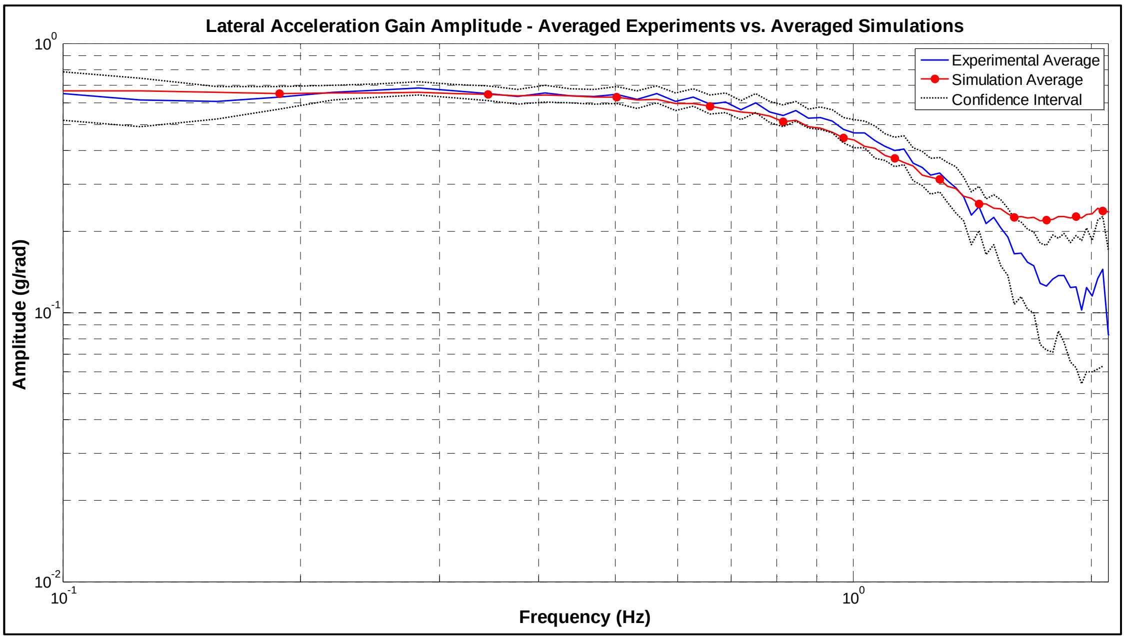

Figure 4.15 Lateral Acceleration Response Gain

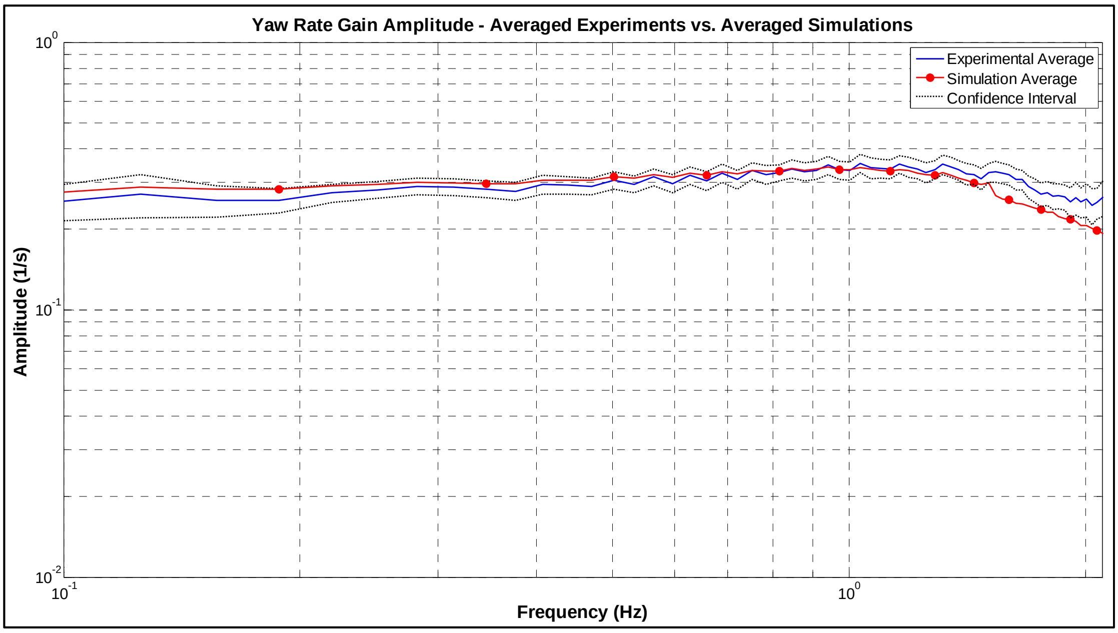

Figure 4.16 Yaw Rate Response Gain

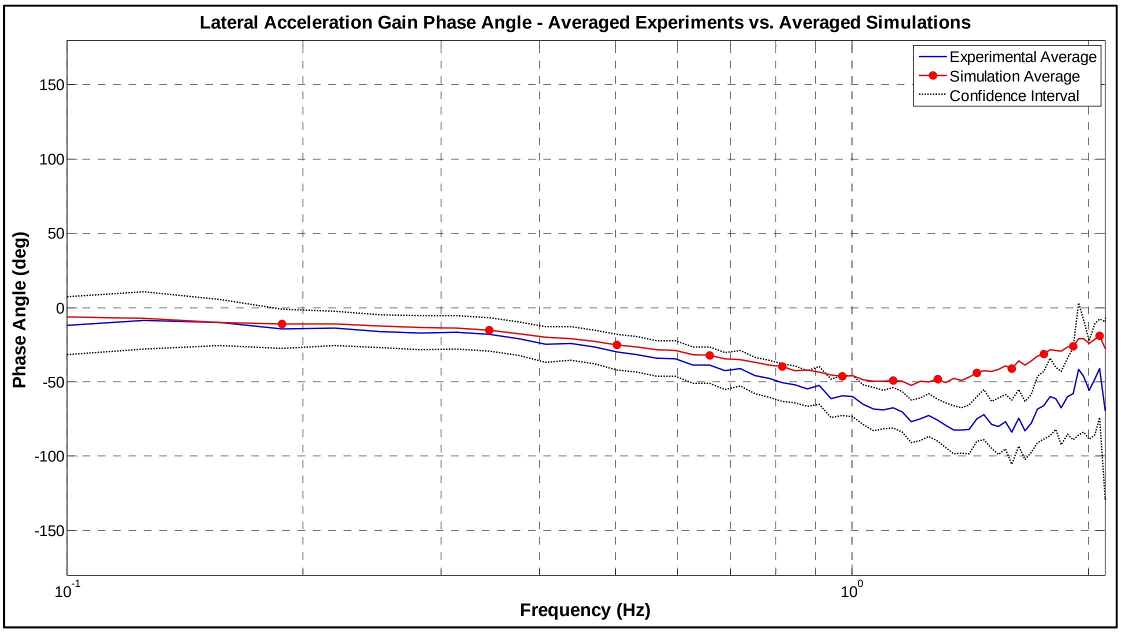

Figure 4.17 Lateral Acceleration Phase Angle

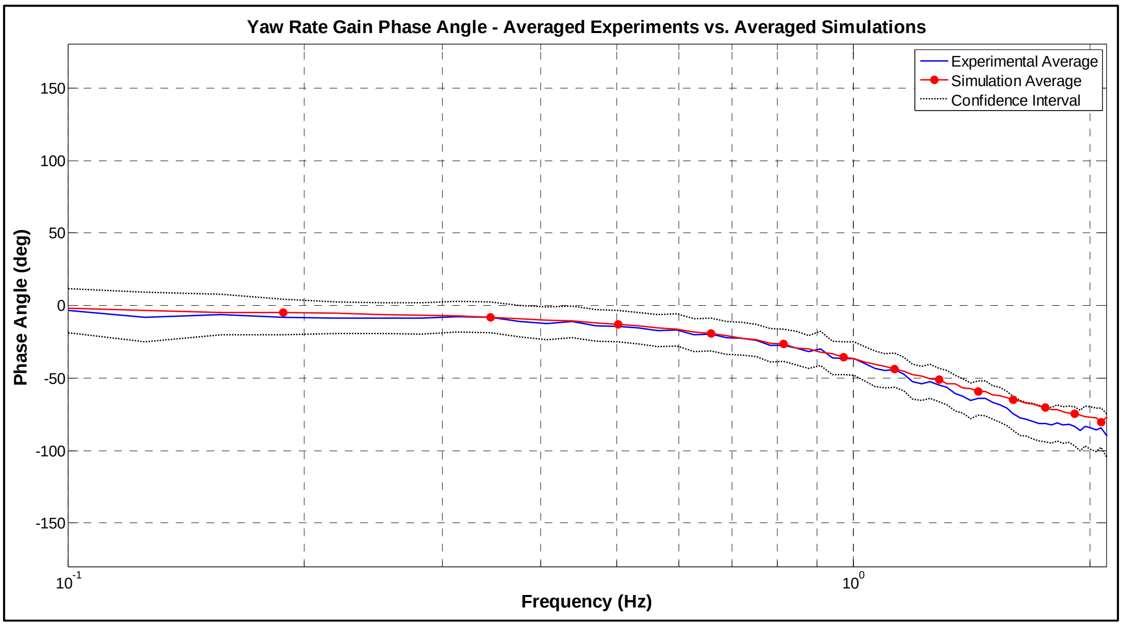

Figure 4.18 Yaw Rate Phase Angle

Discussion of the Results

According to the gain curves; the lateral acceleration gain stays in confidence interval up to 1.59 Hz, and the yaw rate gain stays in confidence interval up to 1.5 Hz. According to the phase angle information; the phase angle between lateral acceleration and steering wheel angle stays in confidence interval up to 0.93 Hz, where the phase angle between yaw rate and the steering wheel angle stays inside the confidence interval in the entire domain of interest.

These findings invalidate the model for the given 0.2 – 2 Hz interval, since the simulation model's validity metric curves do not stay inside the defined EDZ boundaries throughout the frequency interval of interest. On the other hand, the curves coming from the simulation results are within boundaries until certain frequencies. This implies that, the validity criteria would have been satisfied if those values were defined as the boundary of the frequency of interest. Thus, these frequencies are the validity limits of the simulation model.

Consequently, the amplitude information of the model is valid up to around 1.5 Hz, limit being 1.5 Hz for yaw rate and 1.59 Hz for lateral acceleration, and the phase information is valid up to around 0.93 Hz for lateral acceleration, and all the way to 2 Hz for yaw rate.

Frequency response analysis revealed the short comings of the simulation model. Simulation model is valid until 0.9 Hz. If a steer wheel input faster than 0.9 Hz is introduced, the response of the simulation will be more responsive than the target vehicle (that is it will be more responsive than the allowed error amount), but still the amplitude of the response will match. In other words, if, say, a continuous sine wave input of 1.2 Hz with certain amplitude is introduced, the simulation will predict the amplitude of the response within acceptable deviation, but the lag of the simulation model will be smaller than that of the actual vehicle.

This behavior will hold until around 1.5 Hz. After 1.5 Hz, the simulation's amplitude response will also be outside the accuracy boundaries.

In conclusion, sine sweep test maneuver shows the predictive capabilities of the simulation model is unconditionally valid until 0.9 Hz and valid only for the amplitude between 0.9 Hz and 1.5 Hz. For input frequencies higher than 1.5 Hz, simulation model's predictions are not usable according to the defined validity criteria.

4.5 Double Lane Change Maneuver

In the previous sections, the simulation model was tested against idealized fundamental test maneuvers, which exhibit very important dynamical characteristics of the vehicle in time and frequency domain, but were, nonetheless, not everyday maneuvers that a vehicle is likely to encounter in real world driving situations.

Double lane change maneuver, on the other hand, is a purpose dependent maneuver and simulates an emergency lane change situation, which casually occurs in everyday life. In double lane change maneuver, the vehicle must be steered to the adjacent lane and back, without braking or accelerating. During such a maneuver an understeering, or oversteering, or even a rollover situation can occur.[148]

In this section the methodological aspect of the problem of assessing the validity of a simulation using double lane change maneuver as the experimental data source is dealt with, and data handling process is explained and the application of the methodology is demonstrated.

First, the maneuver time history is analyzed. Problems in handling the obtained measurements and possibilities to assess the maneuver are examined. Techniques to split and align the data are presented and compared. Methodologies to handle the experimental and simulation data are introduced. The last part of the section demonstrates the application and the obtained results.

4.5.1 Data Handling and Analysis Methodology

In this section, data handling methodology is presented. The maneuvers analyzed, different approaches are explored and a methodology to assess the experimental and simulation data is introduced.

Analysis of the Maneuver Time History

Double lane change maneuver approximates the behavior of a vehicle in the case where the driver needs to quickly switch from one lane to the other and back in the face of an emergency. During the maneuver the vehicle might understeer due to saturation tire forces in the front axle, or oversteer, especially during the counter steering phase, or even roll over because of the high lateral acceleration involved which occasionally happens with the vehicles with relatively higher center of gravity. The maneuver generally demonstrates the agility and capabilities of the vehicle in lateral dynamics.

Before ISO-3888/1[149] was issued; emergency lane change maneuver used to be simulated using an open loop sine steering input of one period length.[150,151] The amplitude of the wave affected the maximum lateral acceleration during the maneuver and decided the severity of the maneuver, typically ranging between 0.4 Hz and 1 Hz.[152,149] Typical metrics that were measured using this maneuver are:

- Time lags for the first and second half waves of the maneuver (using cross correlation)

[148] Winner (2007): http://www.welt.de/motor/article1280688/Mercedes-und-der-Elch-Die-perfekte-Blamage.html

[149] ISO - 3888/1 (1999): Test track for a severe lane change manoeuvre

[150] Nisonger et. al. (1981): Transient Directional Response Test Procedures for Automobiles

[151] Draft Proposal for an International Standart (1979): Road Vehicle –Transient Response Test Procedures

[152] Heydinger et. al. (1990): A Methodology for Validating Vehicle Dynamics Simulations

- Ratio of the time lags
- Maximum output to maximum input ratios for half waves
- Ratio of the maximum output to maximum input ratios for half waves

These metrics are computed separately for each experimental run and then mean values and standard deviations are calculated. The state of the art standard used to simulate an emergency lane change is ISO-3888/1. In this document, only the test track is defined. That means the resulting maneuver is a closed loop maneuver, in which the test driver tries to follow the defined test track, contrary to its proposed forerunners which define only the shape of the steering input regardless of the track.

The general time history of an emergency lane change maneuver, executed at 80 km/h on a test track defined according to ISO-3888/1 shows that the trend of the input steering wheel angle is comprised of two distinct wave like motions: the first one is from when the vehicle leaves its original lane to when the vehicle reaches the second lane; the second one is from when the vehicle leaves the second lane to when the vehicle returns to its original lane.

Assuming that the velocity is held constant (depending on the aim of the experiment, speed drop can also be counted among possible performance metrics) the frequency and amplitude of these two motions should be very similar. However depending on the selected velocity value, the portion in the middle shows different characteristics as can be seen in Figure 4.19. Nevertheless, just like the open loop single sine input case, the time histories can be investigated in two portions.

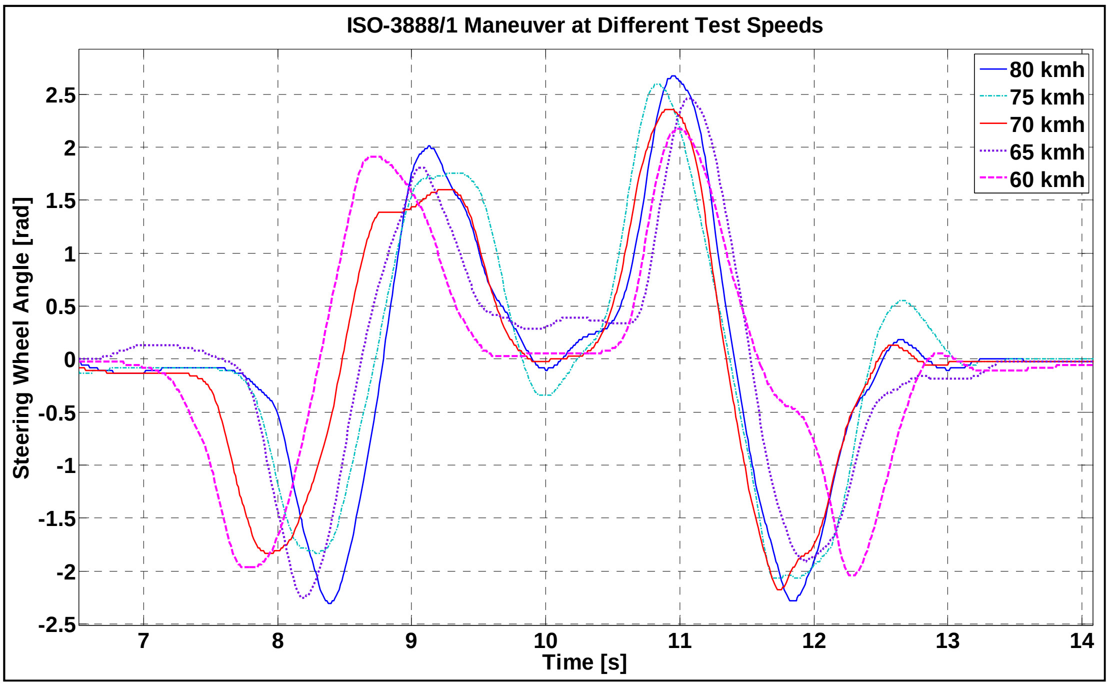

Figure 4.19 Time histories of double lane change maneuver for different test speeds

Data Splitting Options

Depending on the test conditions (road, tire, vehicle type) and vehicle speed, the steering wheel angle can:

a. Reach a steady state in the middle portion of the maneuver (Figure 4.20).
b. Reach a local extremum in the middle portion of the maneuver (Figure 4.21).
c. Reach multiple local extrema in the middle portion of the maneuver, when the vehicle is in the second lane (Figure 4.22).

According to these possibilities one can define the midpoint(s) relatively as:

a. Start and end of the steady state region, starting point being the end time for the first portion and end point being the start time for the second portion (Figure 4.20).
b. Where the single local extremum occurs (Figure 4.21).
c. The first and the last local extremum, first being the end time for the first portion and last being the start time for the second portion (Figure 4.22).

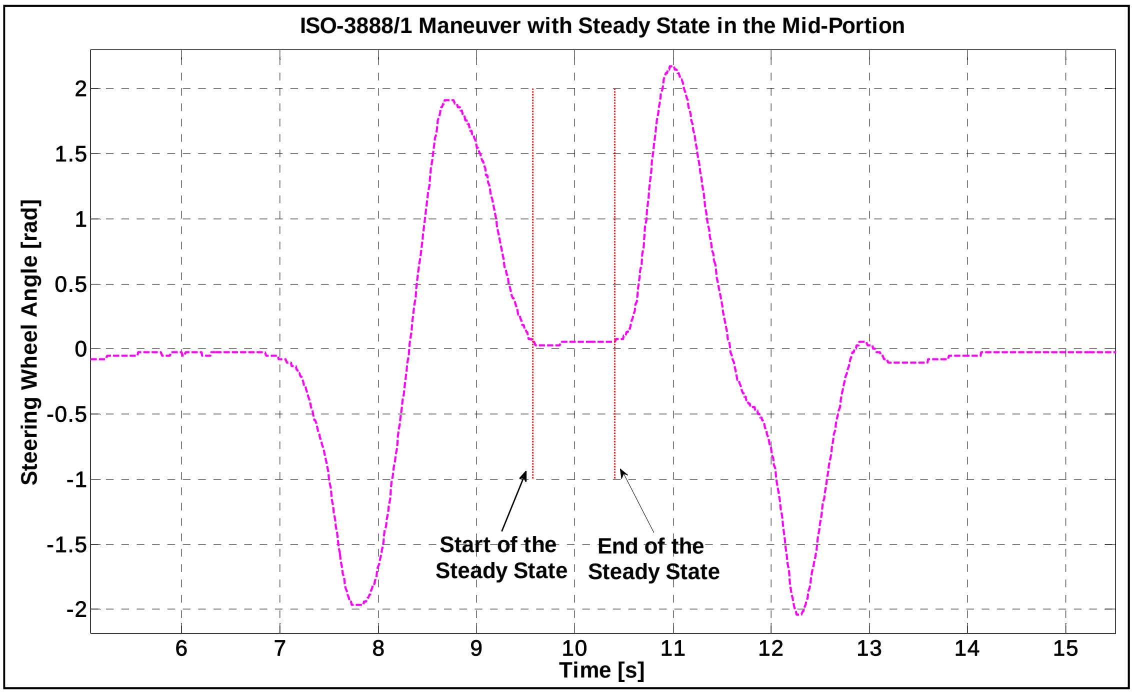

Figure 4.20 Double lane change maneuver with steady state in the mid-portion

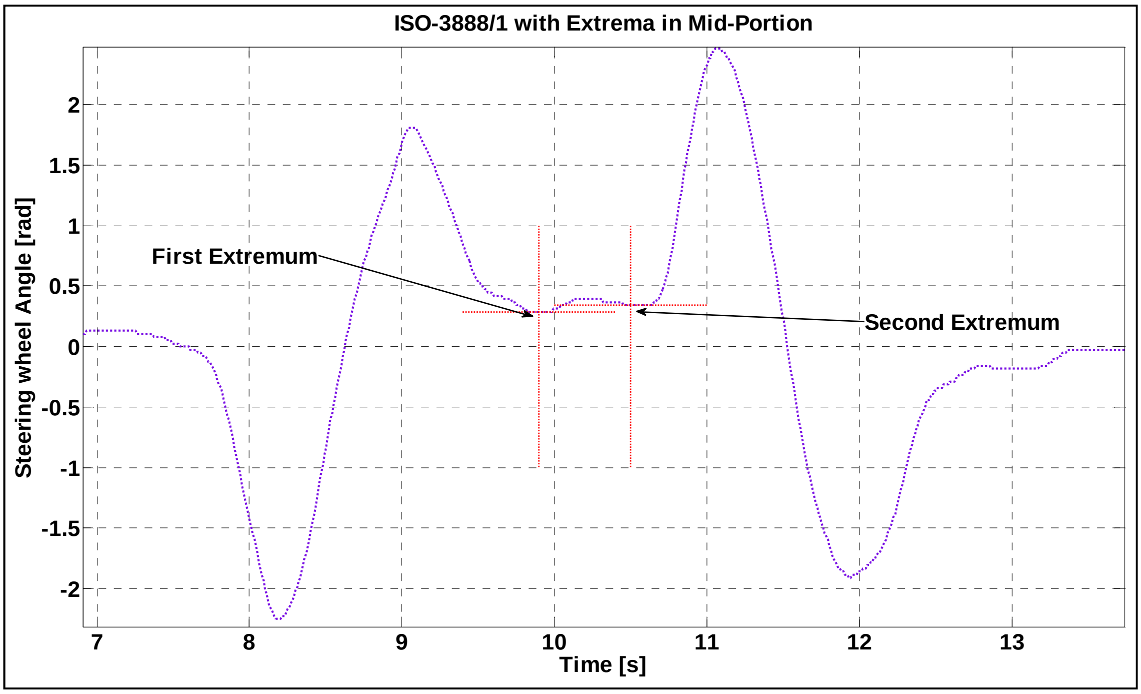

Figure 4.21 Double lane change maneuver with multiple local extrema in the mid-portion

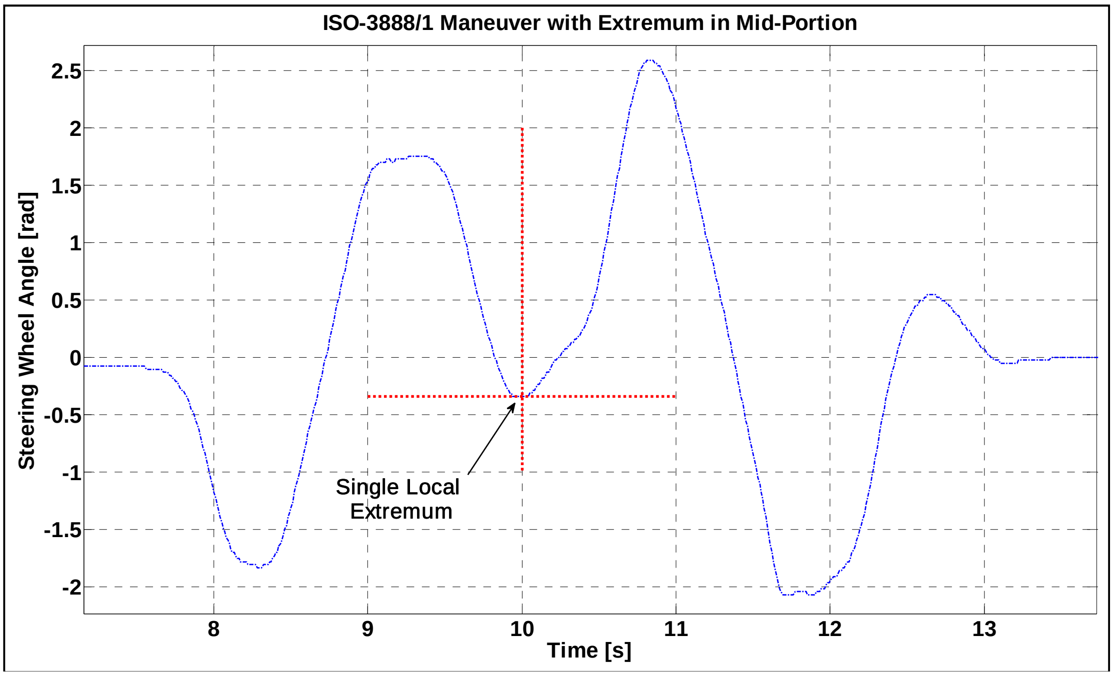

Figure 4.22 Double lane change maneuver with steady state in the mid-portion

All these three techniques are dependent on the conditions in the middle portion of the maneuver and the definition of the reference point(s) requires an experiment dependent approach. On the other hand only the number of experiment to experiment consistent characteristics is limited: entry straight driving, first sine-like input (with two extrema), second sine-like input (with two extrema) and exit straight line driving.

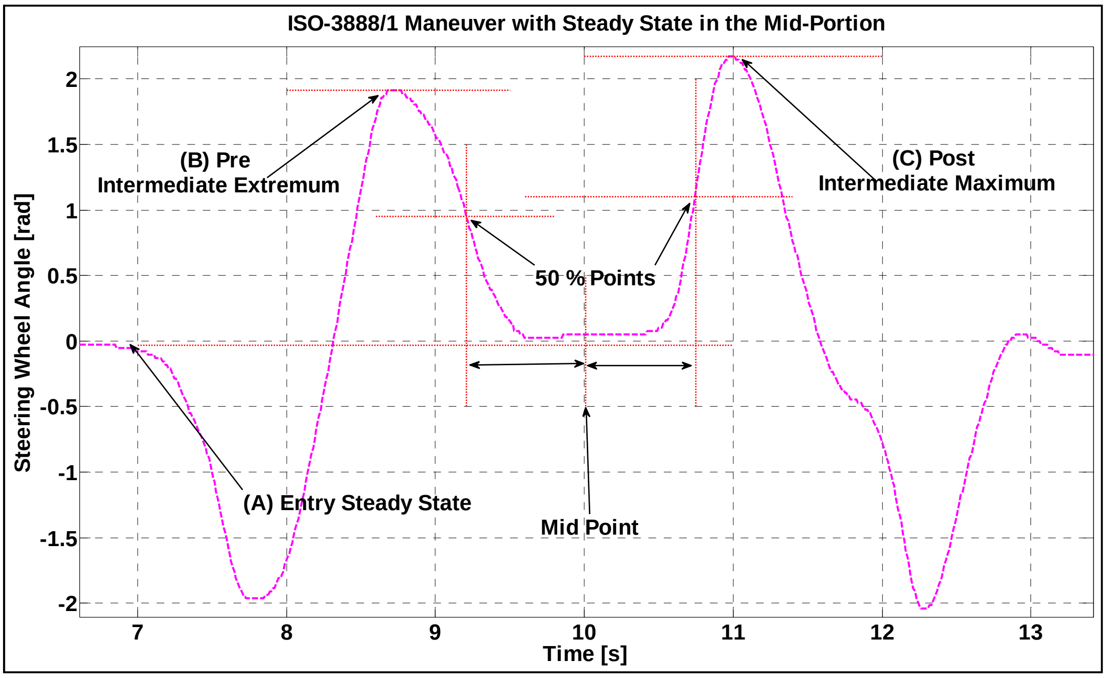

Figure 4.23 Definition of the reference point for data splitting

Since the exit of the maneuver includes stabilizing the vehicle as the vehicle enters the exit lane, the entry straight driving is the only objective and experiment independent steady state property. Thus, if the reference point in the middle portion can be defined using this characteristic value together with one or more of the other experiment independent characteristic points, an objective and experiment independent definition of a reference point for data splitting can be reached.

The proposed method to define the reference point requires three of the aforementioned characteristic values (Figure 4.23): steady state entry steering wheel angle (A), the last extremum of the steering wheel angle before the middle portion (B), the first extremum of the steering wheel angle after the middle portion (C).

- 50% descend time of the first input wave is defined using (A) and (B). This is the time when the steering angle reaches mean value of (A) and (B) before the intermediate portion.
- 50% ascend time of the second wave is defined using (A) and (C). This is the time when the steering angle reaches mean value of (A) and (C) after the intermediate portion.
- The mean value of these two time values is defined as the reference point to split the data.

Such a definition of reference value makes use of the experimental independent characteristic values and is more robust than the previously mentioned techniques. Steady state entry steering wheel angle is calculated using the same approach explained in section 4.3.2.

Once the reference point is defined to split the data the following metrics can be defined:

- Overall lag
- Lags, and ratio of the lags for two portions of the data
- Ratios of maximum outputs and inputs, and the ratio of ratios.

Alignment of Time Histories

Aligning the data is not needed to define and calculate performance metrics for separate test cases, but aligning the outputs of different test runs can be utilized to statistically generate an experimental data zone by calculating the mean values and standard deviations (and thus the confidence intervals) of different test runs at each time step. This EDZ can be used to check if the time histories of the simulation outputs remain inside them, which is previously proposed as a validity criterion.[153]

In order to align the data, a reference point is needed for each part of the split data. For example, in a step response experiment, the time point at which the steering wheel angle reaches 50 % of its final value is used to define relevant time domain performance metrics and to align different test results. In the double lane change maneuver, the steering wheel angle does not reach the steady state except at the start and the end of the maneuver (although a steady state can possibly exist in the middle portion depending on the test conditions, i.e. low speed, different track dimensions, different vehicle).

As mentioned above, a midpoint needs to be defined in order to split the data for cross-correlation analysis. Thus, instead of seeking a general reference point to align the whole time history, it is more logical to find two reference points for the former and latter portions of the data and analyze these portions separately.

This reference points can be defined as:

a. Time at which the steering wheel angle reaches 50 % of its first maximum value for the first portion, and mean value between the entry steady state value and the first extremum after the midpoint for the second portion (Figure 4.24). In the first portion, this point is between the steady state value attained at the entrance area of the track and the first maximum of the steering wheel angle. In the second portion, this point is between end of the transition region and the consequent extremum of the steering wheel angle that is attained as the vehicle leaves the middle lane towards the exit area of the track. This approach is similar to the alignment method of the step input maneuver.[154]

[153] Heydinger et. al. (1990): A Methodology for Validating Vehicle Dynamics Simulations

[154] ISO - 7401 (2003): Lateral transient response test methods

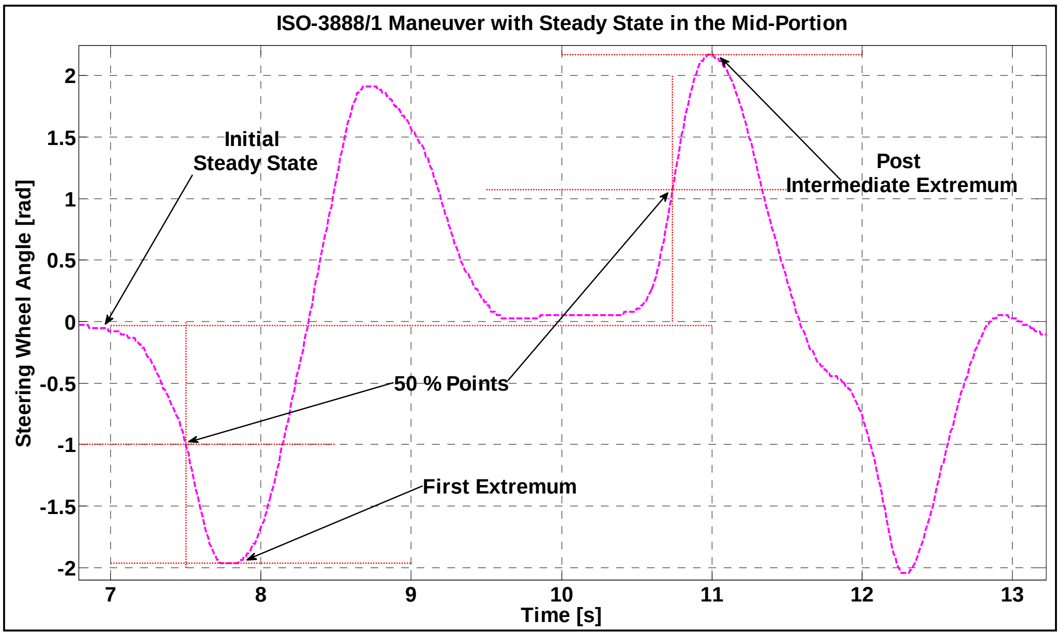

Figure 4.24 Definition of reference points according to (a)

b. Time at which the steering wheel angle reaches the mean value of the first and second extrema for the first portion, and the last and second to last extrema for the second portion. In this case, different from (a), the metrics should be defined using the time differences on either side of the reference points (Figure 4.25).

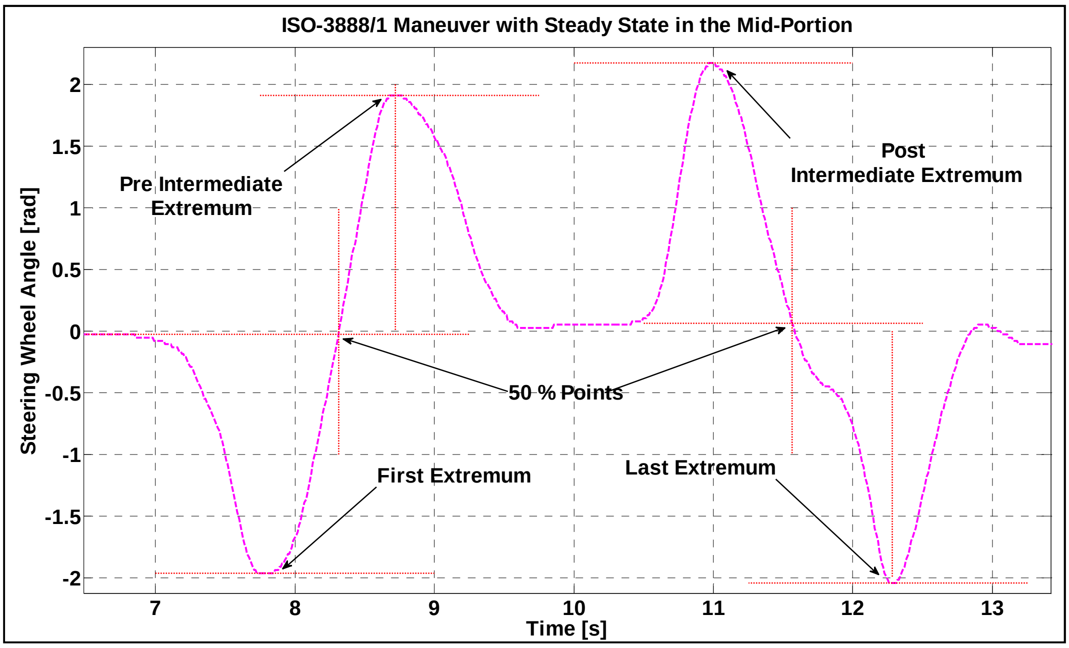

Figure 4.25 Definition of reference points according to (b)

Once the data alignment is completed, confidence intervals and other performance metrics, such as the time coordinates of the maximums with respect to the reference times can be defined.

It should be noted that, another, and considerably simpler, approach would be, instead of taking two separate portions to define the experimental data zone, simply use the first reference point defined in (a) in order to analyze the whole time history.

The opinion of the author of this document is that the maneuver has two distinct portions. The first portion of the maneuver is independent of the second portion, and the second portion of the maneuver is not a natural extension of the first maneuver, like the second half period of a sine, but a consecutive and similar maneuver with its own characteristics. Because of these properties, the maneuver should be analyzed in two portions.

It should also be noted that, the two portions are connected in the manner that the second one is executed immediately after the first one and because of this; the initial conditions of two portions are different. The resulting dynamics from the first portion may propagate into the second portion, whereas the first portion starts from a steady state straight line driving condition.

Experimental Data

Once "enough" number of test maneuvers are performed and experimental data are collected, the recorded input time history is used to run the simulations. The response of the real system as well as the output of the simulations need to be handled, i.e. split and aligned, in order to be able to perform further statistical analysis.

The techniques to split and align the data and the possible metrics to be regarded are presented in the previous section. The proposed methodology, Figure 4.26, can be summarized as:

- Calculating the overall lag
- Defining the midpoint and splitting the data
- Lags, and ratio of the lags for two portions of the data
- Ratios of maximum outputs and inputs, and the ratio of ratios
- Defining reference points for data alignment
- Calculating other metrics, average outputs and confidence

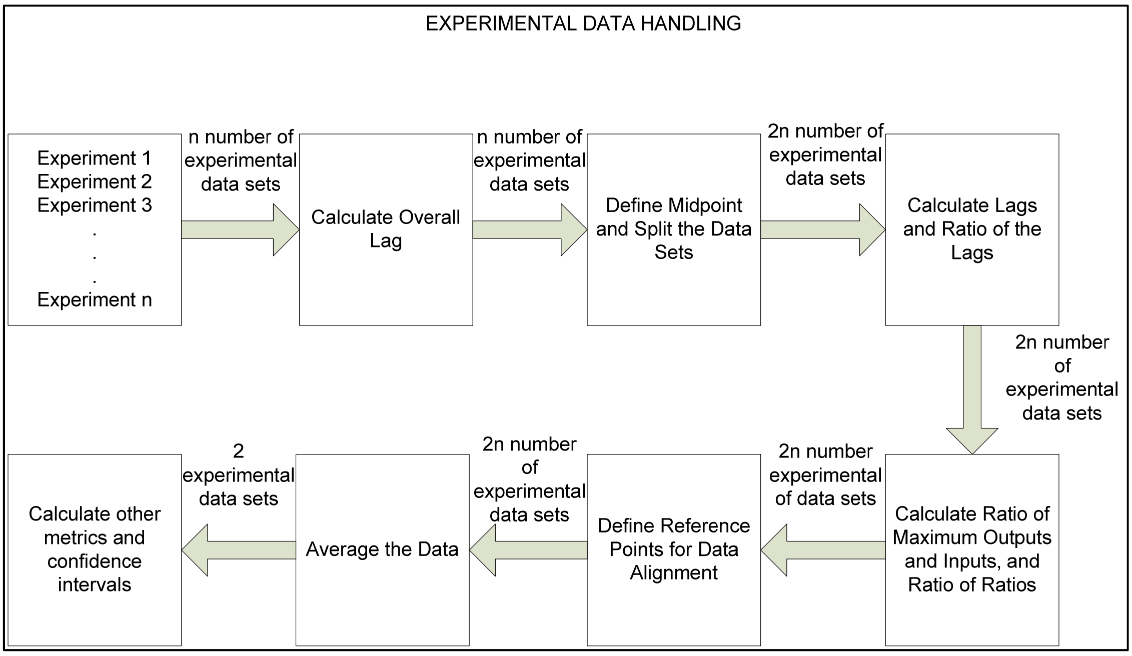

Figure 4.26 Flow diagram of the experimental data handling method

Simulation Data

The simulations are run using the experimentally measured input data. The start and end conditions of the input data is defined using the steady state criterion. Each experimental run is analyzed using a previously written MATLAB® function to find out the regions in which the signal is steady state.

In simulation data handling, there are three possible paths to follow, depending on if the experimental inputs are first reduced to an averaged simulation input and if the data analysis is performed using one interval, or two intervals. A summary of these paths are shown in Figure 4.27.

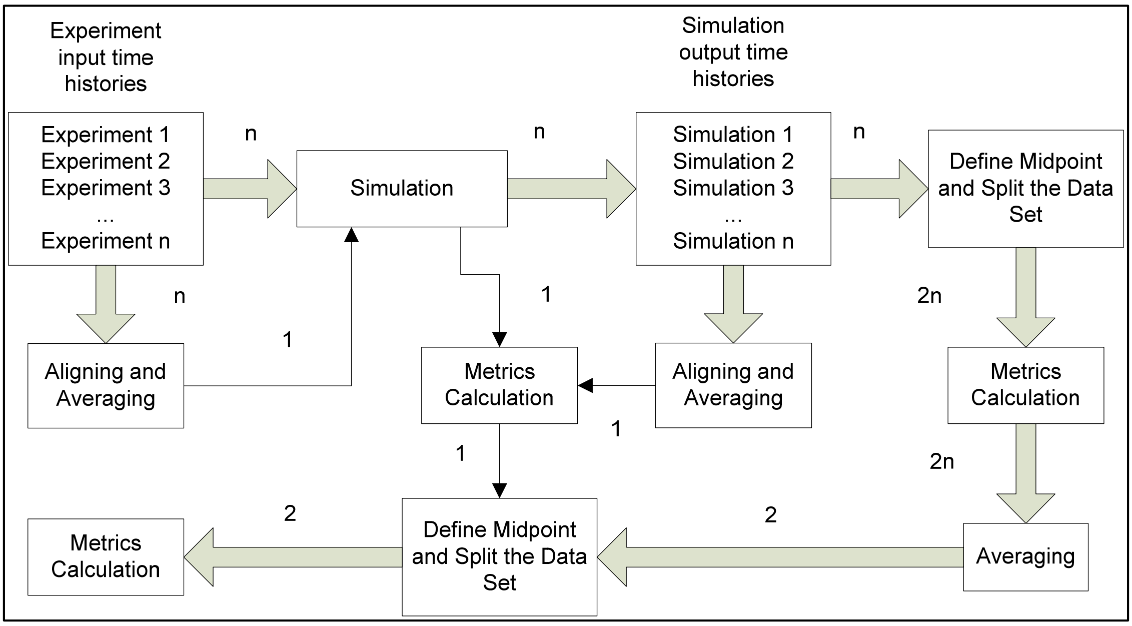

Figure 4.27 Summary of simulation data handling methods

Averaged Input Case

The experimental inputs can be aligned and averaged to obtain an average input time history which yields one simulation time history. This simulation time history is not the average of individual simulations, but the result of a simulation run by using the average time history of the measured input signals. The order of operations in this case is:

- Aligning and averaging the inputs and running the simulation
- Calculating overall lag and other metrics
- Defining the midpoint and splitting the data
- Calculating lags, and ratio of the lags for two portions of the data
- Ratios of maximum outputs and inputs, and the ratio of ratios

Figure 4.28 shows the flow diagram of for this case. This method is appropriate for complex simulation models for which performing only one simulation is more feasible than processing each experimental input one at a time. The other option is running simulations separately for each experimental measurement and then handling the data. These options are explored in the following two sections.

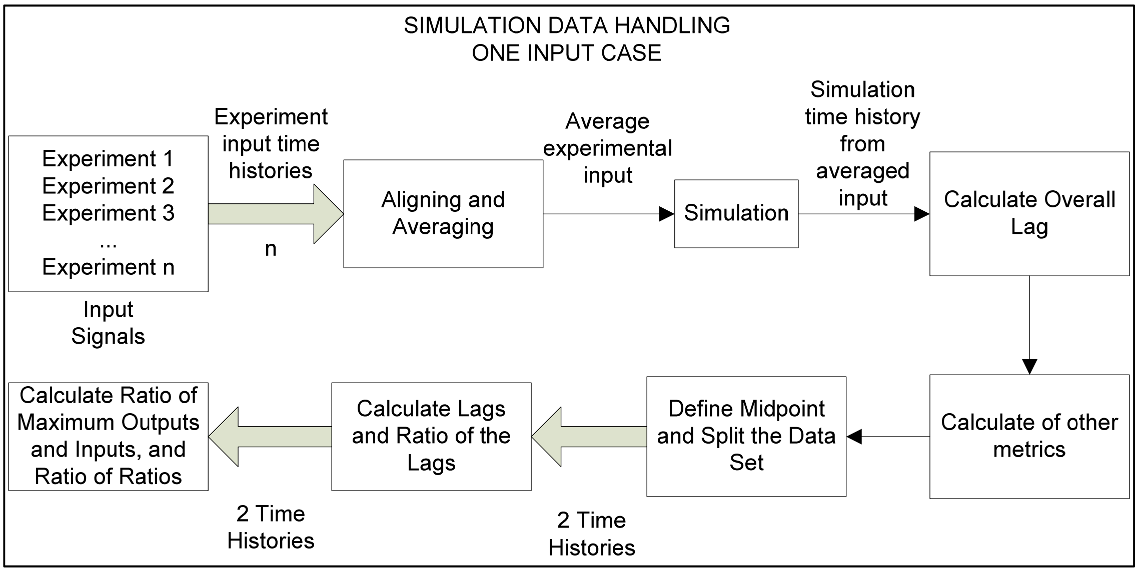

Figure 4.28 Simulation data handling method for averaged input case

Averaged Output One Interval Case

This case explores the possibility to perform a simulation for each maneuver measurement and then averaging the outputs and assessing the metrics using one reference point for alignment. Steps in this case are:

- Defining the reference point for each data set
- Averaging the data sets
- Calculating overall lag and other metrics
- Defining the midpoint and splitting the data

- Calculating lags, and ratio of the lags for two portions of the data
- Ratios of maximum outputs and inputs, and the ratio of ratios

This case is demonstrated in Figure 4.29.

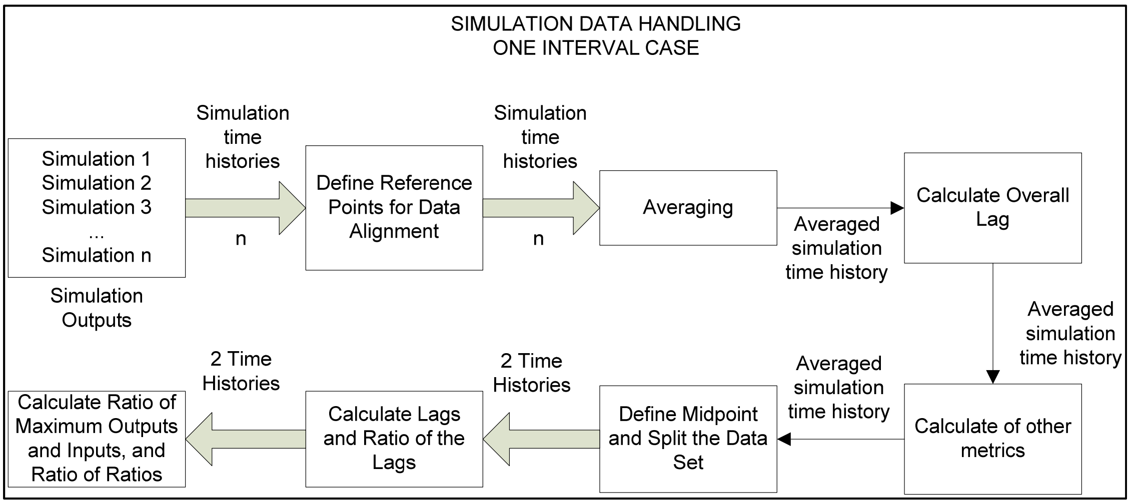

Figure 4.29 Simulation data handling method for averaged output one interval case

Averaged Output Two Intervals Case

In this case the simulation is performed for each maneuver measurement and then the outputs are averaged. Assessment of the metrics is done using two reference points for alignment.

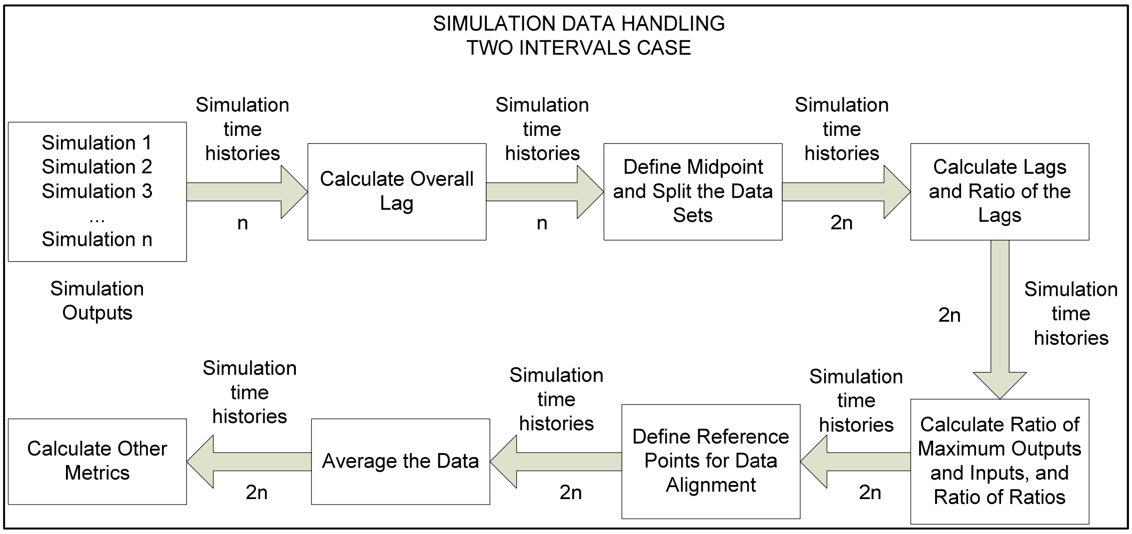

Figure 4.30 Simulation data handling method for averaged output two intervals case

The proposed methodology, Figure 4.30, can be summarized as:

- Calculating the overall lag for each case
- Defining the midpoint and splitting the data for each data set
- Calculating Lags, and ratio of the lags for two portions of each of the data sets
- Ratios of maximum outputs and inputs, and the ratio of ratios of each of the data sets and then averaging

- Defining the reference points for data alignment and averaging
- Lags, and ratio of the lags for two portions (optional)
- Ratios of maximum outputs and inputs, and the ratio of ratios (optional)

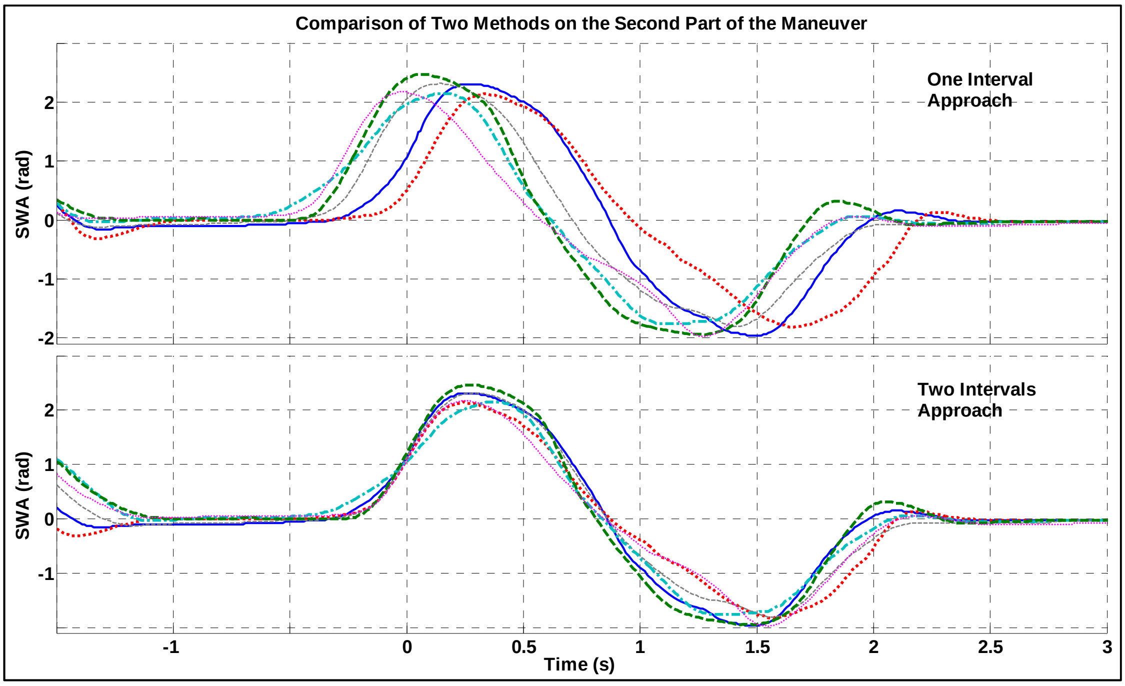

Figure 4.31 Comparison of one interval and two intervals approaches

The first of these methods should only be followed if the simulation model is very complex or running separate simulations for each experiment is not feasible due to required workload, time or costs. Of the latter two methods which are compared in Figure 4.31, the two interval method captures the two distinct portions of the maneuver and provides more comparable and better defined metrics. Table 4.11 presents the average of measured steering wheel angle magnitudes and temporal coordinates at the third and the fourth extrema for the data sets shown in Figure 4.31.

Table 4.11 Temporal and spatial coordinates of the third and fourth extrema, calculated with the one and two interval approaches

Average Steering Wheel Angle	Third Extremum		Fourth Extremum	
	One Interval	Two Intervals	One Interval	Two Intervals
Time in s	0.2	0.3	1.35	1.55
Amplitude in rad	2.086	2.237	-1.689	-1.862

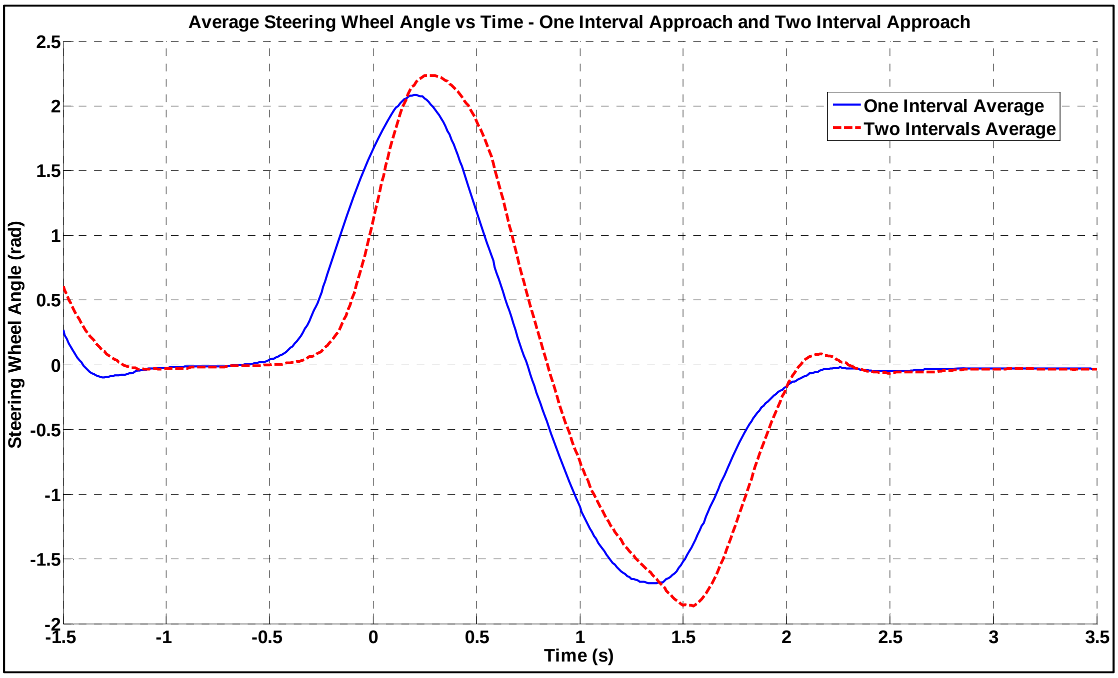

Figure 4.32 Comparison of Average Steering Wheel Angles

When Figure 4.31 is examined, it is seen that the lowest steering wheel angle amplitude is 2.15 radians for the third extremum, and -1.75 radians for the fourth extremum. Comparing these figures with Table 4.11, it is clear that one interval approach performs poorly in aligning the input signal in the second part of the maneuver. This behavior is illustrated in Figure 4.32 where averaged steering wheel angle signals for one interval and two intervals cases are presented.

Validity Criteria for the Case Study

General metrics for assessment of double lane change maneuver is explained in the previous section. In this section the validity criteria to be imposed on these metrics are presented. The validity of the simulation model regarding the double lane change maneuver is assessed by checking the amount of error between the metrics calculated using the experimental measurements and simulation results, much like the step response maneuver. Clearly, it cannot be expected that the simulation metrics will be exactly equal to experimental metrics.

The metrics to be used are chosen as:

- Time lags for the first and second half waves of the maneuver is to be computed for each experimental and simulation data set using cross correlation.
- Peak times for each of the extrema.
- Magnitudes of all four extrema for each data set.
- EDZ visual graphics comparison

Time lags are calculated used cross correlation according equation 4.10. The integral of the multiplication of the input and the lagged output signals are checked for a range of lag values, and the amount which maximizes the integral is determined.

$$R_{fg} = \int f(t) \cdot g(t + \tau) dt \qquad 4.10$$

This time lag value is calculated for each experiment and simulation data set pairs, as well as the average of the experiment and simulation data sets and 95 % confidence intervals are calculated. The validity condition for this metric is computed error interval ±0.05 seconds. Since the time values are already near to zero an absolute acceptance band is used.

The second temporal validity metric is the peak times for each of the extrema. Much like the peak time analysis of the step response maneuver, these metrics are calculated for each case separately and also for the averaged case, and 95 % confidence intervals are imposed. The error allowance for validity is determined to be 0.05 seconds for average of metrics case and 0.1 seconds for the metrics of the averaged outputs case. Percentage allowance in this case is again impractical, since the expected values for temporal metrics are around 0.5 seconds for the first extremum and 1.5 seconds for the second extremum, and application of a percentage allowance would cause the tolerance band for the second extremum be three times wider.

Magnitude metrics are analyzed using the same principles. A 5 % error interval is added to the top of the 95 % confidence bands when comparing the average of the metrics. Comparison of the averaged data signals are also performed using a 5 % error allowance.

Lastly, the averaged output signals from experiments with their relative confidence intervals are to be visually inspected, as in the step response maneuver. In this visual graphical comparison, the EDZ is plotted on the same diagram with the averaged simulation output. Due to the severe transient nature of the maneuver, this comparison is not subject to any validity criteria as was in the step response maneuver, but is aimed to assist in determining where the simulation performed weakly. Metric validity windows for all four extrema are to be inserted to this graphic, so that the actual positions can be compared with those of the averaged cases.

4.5.2 Application and Analysis

In this section the application of the previously introduced methodology is demonstrated. The experimental measurements are used to run the simulation. Then the experimental and simulation data are processed according to the flow diagrams in Figure 4.26 and Figure 4.30. The validation metrics are calculated and EDZ's and MVW's are generated. Significance of the findings is discussed at the end of the section.

Experimental Data

All experiments are performed at 60 km/h (± 2 km/h) on the track the dimensions of which are defined by the standard.[155] The vehicle is accelerated to the aimed test speed, and cruise control system of the vehicle is engaged. Driver guided the vehicle through the test track, keeping the steering wheel movements as smooth as possible in order to minimize experiment to experiment differences. This process is highly dependent on the test driver's experience and abilities, but with practice results with adequate quality are obtained.

The quality of the experiments is checked on the site by the tester immediately following the maneuver. In double lane change maneuver; existence and consistency of the initial and final steady state conditions and the smoothness of the steering input are the important criteria for a successful experimental case. The latter of these criteria is totally subjective and is assessed by the test driver.

Obtained experimental measurements are saved as *.mat* files. Parameters that are not included in the *.mat* file are reported in the experiment protocol. A total of 6 experiments are chosen for simulation and validity analysis.

Simulation Data

Experimental measurements are processed using MATLAB® and Excel® and a text file with time vector and steering wheel angle magnitudes is generated for each experiment. The simulation package IPG CarMaker® uses this text file in order to synchronize the steering wheel angle input with the simulation time.

Standard driver settings are used when simulating the double lane change maneuver. Experimental parameters are read from the experimental protocol. The geometry of the test track is not modeled and the simulation road is defined as a sufficiently wide and long paved surface.

Simulation model ran on a straight line until the defined maneuver speed is reached, and then the supplied text file is used to manipulate the steering wheel angle. Simulation results are also saved as *.mat* files using CarMaker® for Simulink®.

Data Handling

Data handling is performed according to the methodology explained in section 4.5.1. A mid-point is determined using the second and the third extrema, and the initial steady state value for each steering wheel angle measurement and the data sets are divided into two. Then the steering wheel angles, lateral accelerations and yaw rates of each

[155] ISO - 3888/1 (1999): Test track for a severe lane change manoeuvre

experimental and simulation data set are aligned with respect to the point at which the steering wheel angle reaches the 50 % of the first extremum. The modification of the data is performed using linear interpolation. The process is performed between each data point, spaced with 0.01 seconds, and causes negligible error.

Metrics

The analysis of time lags determined through cross correlation for each of the experimental and simulation cases, for the first and second sections of the maneuver are shown in Table 4.12. In order to calculate the 95 % confidence intervals, Student's t-distribution is used.

The average of the computed time lags all fall within 0.05 seconds of the experimental time lags, and therefore satisfy the first validity criterion. The time lags of the averaged data are presented in Table 4.13. Just like the previous case, all of the estimated time lags of the simulation fall within 0.05 seconds of the calculated experimental time lags, and the simulation model passes this validity criterion with flying colors.

Table 4.12 Statistical Analysis of Time Lag

	Lateral Acceleration Time Lag in s		Yaw Rate Time Lag in s	
	First Half	Second Half	First Half	Second Half
Average of Experimental Metrics	0.083	0.132	0.053	0.085
Upper Bound	0.114	0.140	0.084	0.094
Lower Bound	0.053	0.124	0.022	0.076
Average of Simulation Metrics	0.113	0.170	0.052	0.093
Error Percentage	36	29.11	3.13	9.80
Absolute Error	0.03	0.038	0.002	0.008
Result	PASS	PASS	PASS	PASS

Table 4.13 Time Lag for Averaged Experiment and Simulation

	Lateral Acceleration Time Lag in s		Yaw Rate Time Lag in s	
	First Half	Second Half	First Half	Second Half
Metrics of Average Experiment	0.09	0.14	0.06	0.09
Metrics of Average Simulation	0.13	0.18	0.05	0.09
Error Percentage	44.44	28.57	16.67	0
Absolute Error	0.04	0.04	0.01	0
Result	PASS	PASS	PASS	PASS

The second temporal validity metric is the time values of the extrema. In Table 4.14 and

Table 4.15, statistics for time values of the extrema for lateral acceleration and yaw rate, respectively, are presented. The simulation's performance for this metric is better for lateral acceleration than it is for yaw rate. Although all of the simulation metrics fall within the defined performance band, especially the fourth extremum time of the yaw rate is acceptable only by 0.01 seconds.

Table 4.14 Statistical analysis of the lateral acceleration extrema temporal coordinates

	Lateral Acceleration Extrema Times in s			
	First	Second	Third	Fourth
Average of Experimental Metrics	0.51	1.56	0.51	1.693
Upper Bound	0.591	1.662	0.573	1.774
Lower Bound	0.43	1.458	0.447	1.612
Average of Simulation Metrics	0.532	1.605	0.53	1.648
Error Percentage	4.25	2.88	3.92	2.66
Absolute Error	0.022	0.045	0.02	0.045
Result	PASS	PASS	PASS	PASS

Table 4.15 Statistical analysis of the yaw rate extrema temporal coordinates

	Yaw Rate Extrema Times in s			
	First	Second	Third	Fourth
Average of Experimental Metrics	0.425	1.425	0.457	1.61
Upper Bound	0.492	1.589	0.556	1.77
Lower Bound	0.358	1.261	0.358	1.45
Average of Simulation Metrics	0.433	1.333	0.393	1.46
Error Percentage	1.96	6.43	13.87	9.21
Absolute Error	0.008	0.092	0.063	0.14
Result	PASS	PASS	PASS	PASS

On the other hand, the extremum time metrics of the averaged cases, presented in Table 4.16. and Table 4.17, have much lower amount of error. Thus, the temporal coordinates of the extrema are all within defined validity intervals. Naturally, these metrics must be combined with the spatial coordinates of the extrema so that the complete coordinates of the metrics can be determined.

Magnitudes of the extrema are the spatial validity metrics to be checked. According to the findings presented in Table 4.18 and Table 4.19, the simulation model succeeds in reproducing the response magnitudes in all of the extrema except for the third. The amount of error on the third extrema is 0.118 g for the lateral acceleration (equivalent to 12.18 %) and 0.128 rad/s for the yaw rate (equivalent to 20.37%). It should be noted that the magnitude of the lateral acceleration of the third extremum is 16.5%, and the magnitude of the yaw rate of the third extremum is 22.5% higher than that of the fourth extremum, which has the next highest magnitude for both responses.

Table 4.16 Lateral acceleration extrema temporal coordinates for averaged experiment and simulation

	Lateral Acceleration Extrema Times in s			
	First	Second	Third	Fourth
Metrics of Average Experiment	0.49	1.62	0.50	1.67
Metrics of Average Simulation	0.52	1.61	0.53	1.63
Error Percentage	6.12	0.62	6.0	2.40
Absolute Error	0.03	0.01	0.03	0.04
Result	PASS	PASS	PASS	PASS

Table 4.17 Yaw rate extrema temporal coordinates for averaged experiment and simulation

	Yaw Rate Extrema Times in s			
	First	Second	Third	Fourth
Metrics of Average Experiment	0.42	1.35	0.45	1.66
Metrics of Average Simulation	0.42	1.33	0.39	1.56
Error Percentage	0	1.48	13.33	6.02
Absolute Error	0	0.02	0.06	0.10
Result	PASS	PASS	PASS	PASS

Considering the averaged experimental and simulation data, the results are similar to those of the separately calculated metrics. In Table 4.20 and Table 4.21, maximum response magnitudes for the averaged data are presented. Except the third extremum, the averaged data maximum response magnitudes are within acceptable range. Nearly the same amount of absolute and percentage error is observed in both responses for the third extremum: For lateral acceleration 0.126 g (equivalent to 13.1%) and 0.123 rad/s (equivalent to 19.75 %). Note that the magnitude of the lateral acceleration of the third extremum is 20.9% higher than that of the fourth extremum, and the magnitude of the yaw rate of the third extremum is 23.7% higher than that of the first extremum, which have the next highest magnitude for respective responses.

Table 4.18 Statistical analysis of the lateral acceleration extrema spatial coordinates

	Lateral Acceleration Extrema Magnitudes in *g*			
	First	Second	Third	Fourth
Average of Experimental Metrics	-0.774	0.777	0.969	-0.832
Upper Bound	-0.831	0.85	1.041	-0.895
Lower Bound	-0.717	0.703	0.897	-0.768
Average of Simulation Metrics	-0.804	0.817	0.851	-0.825
Error Percentage	3.82	5.15	12.18	0.88
Absolute Error	0.03	0.04	0.118	0.007
Result	PASS	PASS	FAIL	PASS

Table 4.19 Statistical analysis of the yaw rate extrema spatial coordinates

	Yaw Rate Extrema Magnitudes in rad/s			
	First	Second	Third	Fourth
Average of Experimental Metrics	-0.505	0.443	0.626	-0.511
Upper Bound	-0.555	0.489	0.672	-0.553
Lower Bound	-0.454	0.397	0.58	-0.469
Average of Simulation Metrics	-0.476	0.472	0.499	-0.498
Error Percentage	5.74	6.48	20.37	2.68
Absolute Error	0.028	0.029	0.128	0.018
Result	PASS	PASS	FAIL	PASS

Table 4.20 Lateral acceleration extrema spatial coordinates for averaged experiment and simulation

	Lateral Acceleration Extrema Magnitudes in *g*			
	First	Second	Third	Fourth
Metrics of Average Experiment	-0.767	0.745	0.966	-0.799
Metrics of Average Simulation	-0.801	0.776	0.840	-0.817
Error Percentage	4.41	4.15	13.07	2.28
Absolute Error	0.034	0.031	0.126	0.018
Result	PASS	PASS	FAIL	PASS

The final step in the validity analysis of the double lane change maneuver is the visual graphical comparison of the EDZ with the average simulation output. The aligned steering wheel angle, experimental lateral acceleration and yaw rate signals are averaged for the first move and the second move. 95 % confidence intervals are calculated for output signals using Student’s t-distribution. Simulation results for lateral acceleration and yaw rate are averaged as well. The results are presented in Figure 4.33, Figure 4.34, Figure 4.35 and Figure 4.36.

Table 4.21 Yaw rate extrema spatial coordinates for averaged experiment and simulation

	Yaw Rate Extrema Magnitudes in rad/s			
	First	Second	Third	Fourth
Metrics of Average Experiment	-0.502	0.427	0.621	-0.498
Metrics of Average Simulation	-0.471	0.468	0.498	-0.457
Error Percentage	6.21	9.68	19.78	8.25
Absolute Error	0.031	0.041	0.123	0.041
Result	PASS	PASS	FAIL	PASS

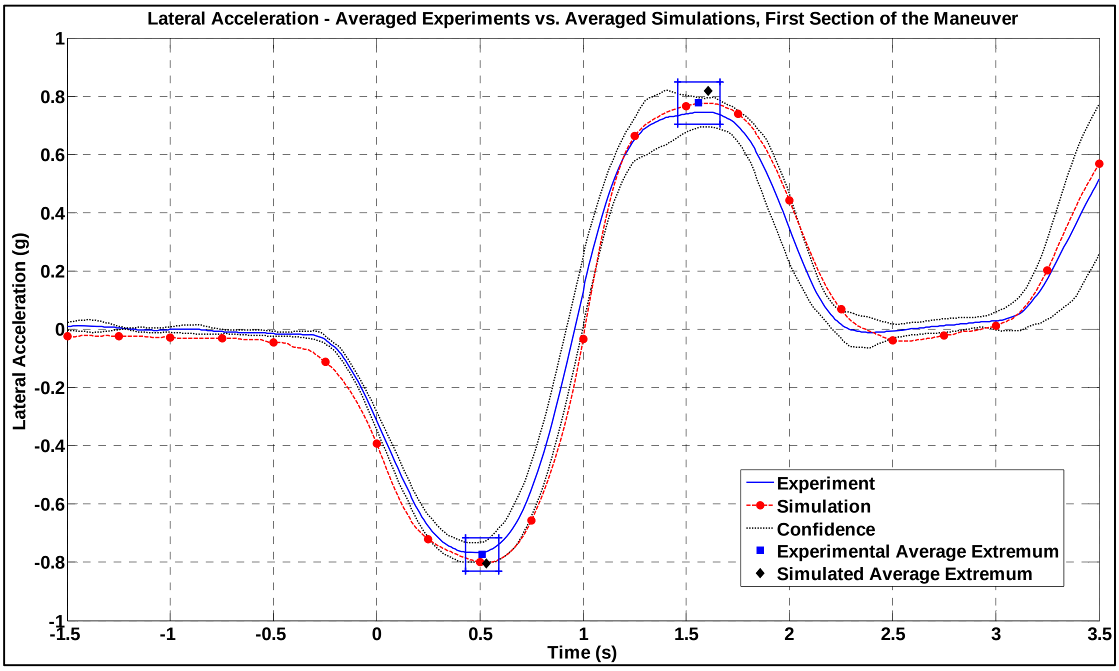

Figure 4.33 Lateral Acceleration EDZ vs. Averaged Simulation – The First Move

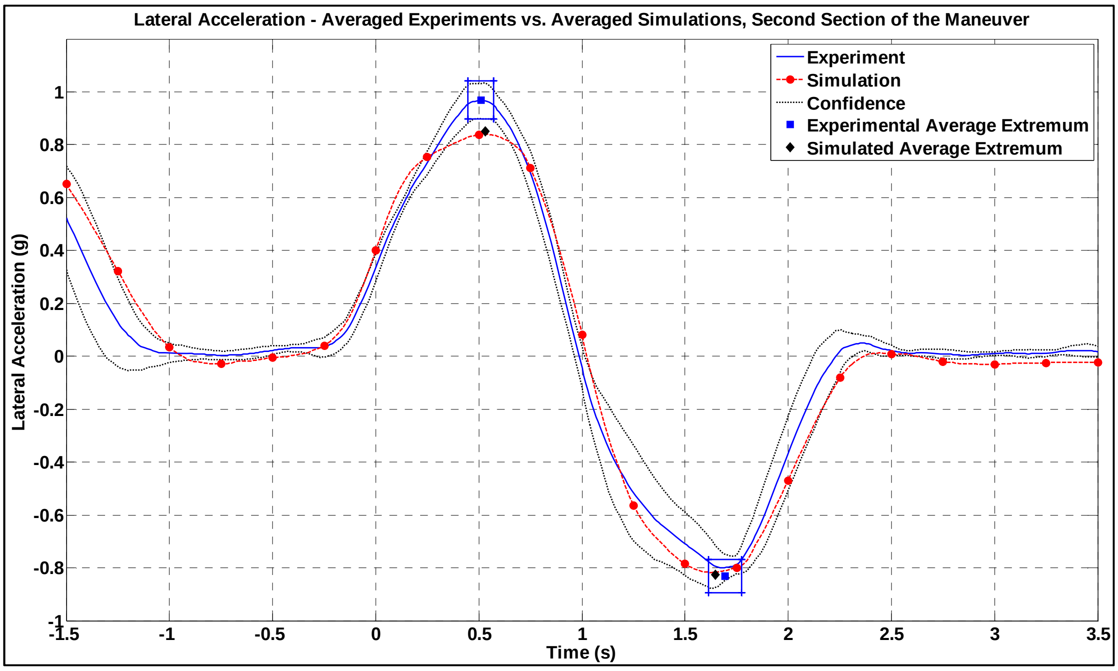

Figure 4.34 Lateral Acceleration EDZ vs. Averaged Simulation – The Second Move

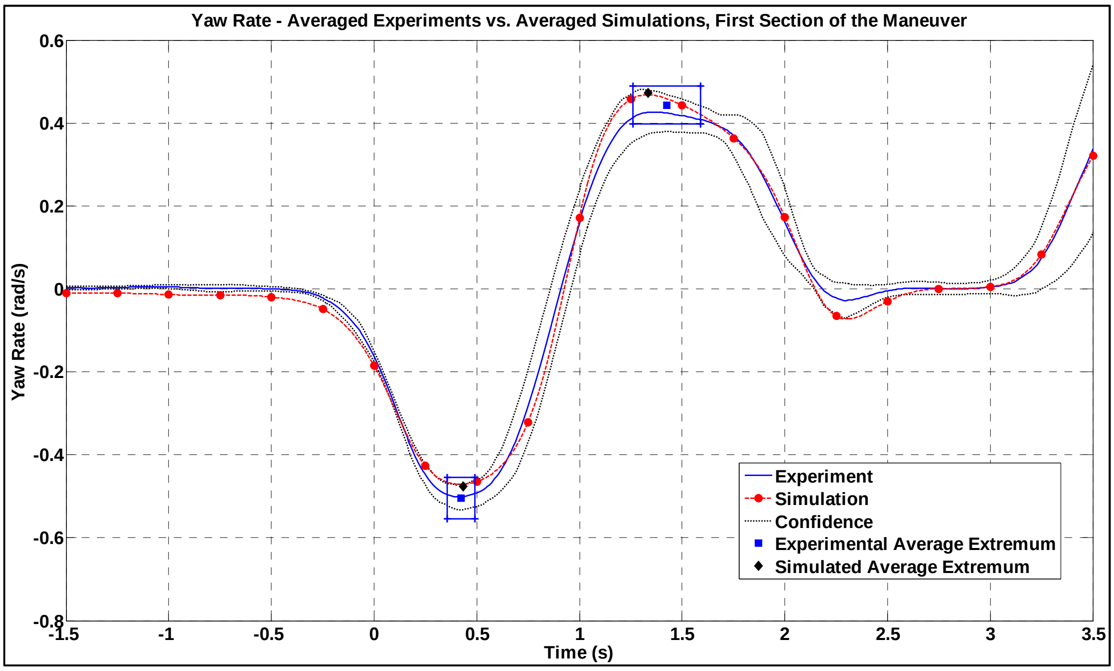

Figure 4.35 Yaw Rate EDZ vs. Averaged Simulation – The First Move

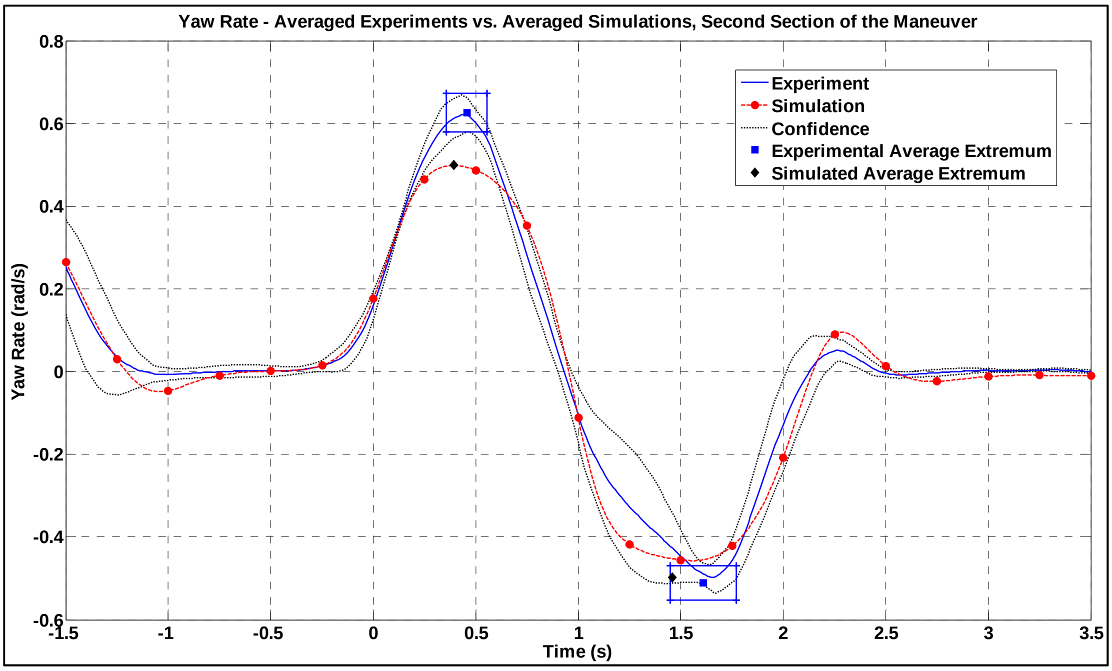

Figure 4.36 Yaw Rate EDZ vs. Averaged Simulation – The Second Move

Discussion of the Results

According to the analysis of the validation metrics, except third extremum, all of the criteria are fulfilled. The same conclusion can be reached when the metrics of the average experiment and simulation are checked.

Analyzing the numerical findings, that particular extremum exhibits more than 20 % higher lateral acceleration and more than 23 % higher yaw rate than the highest of the rest of the extrema. The meaning of this finding is that the simulation's performance is not acceptable for maneuvers with high lateral acceleration and yaw rate demand. This phenomenon is clearly visible in Figure 4.34 and Figure 4.36.

Averaged lateral acceleration and yaw rate signals of the experiments and the simulations are also all in accordance except for the third extremum. The same goes for the metric validity windows as well. The windows indicate that the simulation is not invalid for the first, the second and the fourth extrema.

This failure in simulating the third extremum successfully does not mean that the simulation is generally invalid, but merely defines the limits of the simulation model. The simulation can go only up to roughly 0.45 rad/s for yaw rate and 0.8 g for lateral acceleration. Lateral acceleration response can be simulated up to 0.8 g (fourth extremum) and yaw rate response up to 0.47 rad/s (first extremum); and these values are identified to be the maximum application range for the simulation model in question.

Another simulation shortcoming that can be identified using the EDZ diagrams is that the initial rise of the simulation model is not synchronized with that of the measurements (Figure 4.34). Although in accurate modeling of the lateral relaxation behavior of the tires can contribute to this error, relaxation length affects all of the time history, since the experiments are performed at constant speed using with the cruise control engaged.

From the EDZ diagrams, another clearly observable phenomenon is the lag-lead switching behavior of the simulation model. As the steering wheel angle rate changes sign, i.e. right after the extrema, the simulation model tends to switch from trailing the experimental data to leading the experimental data. This behavior might be caused by the unmodeled hysteresis or again the stiffness of the steering wheel system.

The zero offset of the steering wheel angle is another error source that should be considered. The experimental vehicle exhibits a certain amount of lash, which was not propagated into the simulation model. Steering wheel lash and the resolution of the steering wheel sensor of the vehicle ESC system are the main reasons of this phenomenon.

4.6 Conclusion

In this chapter, the proposed general validation methodology is extended and detailed for three test cases. Step response maneuver, sine sweep maneuver and double lane change maneuver are analyzed, maneuver specific assessment methodologies are derived, and application is demonstrated.

Steady state and transient performance of the simulation model in time domain are tested with step response maneuver. A methodology to objectively determine the reference point for alignment is developed. Metric validity window concept is introduced and explained. Detailed data assessment procedure is established and the application of these techniques to a test case is presented.

The analysis of step response maneuver did not show any unacceptable discrepancy between the simulation model and the test measurements. Both temporal and spatial metrics are within the accuracy limits, and the visual comparison of the averaged simulation to the experiment passed the test as well.

Transient response of the model in frequency domain is tested using sine sweep maneuver. Data handling methodology for frequency analysis is developed. Real and imaginary components of the complex frequency transfer functions are analyzed instead of amplitude and phase information of the measurements, and required formulation is presented.

Simulation model performed rather poor, and is unconditionally invalidated for the frequencies above 1.5 Hz, failing both the amplitude and phase angle criteria. For the frequencies between 0.9 Hz to 1.5 Hz, the amplitude response of the model stays within the computed intervals but the phase angle response of the lateral acceleration does not.

The simulation model is unconditionally validated for the frequencies below 0.9 Hz, under the previously explained assumptions.

Finally a data assessment methodology for double lane change maneuver is developed. The maneuver is divided into two parts, and each part is separately analyzed. Techniques for data partitioning and aligning are explained. Application of the methodology is demonstrated on test case measurements.

Double lane change maneuver revealed another shortcoming of the simulation model. It is shown that the simulation model cannot reliably predict maneuvers which have a lateral acceleration reading higher than 0.8 g and yaw rate higher than approximately 0.5 rad/s. Moreover discrepancies in the maneuver entry zone and a lag-lead behavior between the simulation and the experiment are observed. These effects are concluded to be due to inadequate modeling of the non-linearity effects of the steering system.

In summary the conclusions of this chapter are:

- Maneuvers which are used in demonstration of the application of the validation methodology are selected to show the diverse dynamic behavior and most important cases.
- Individual data assessment and validation methodologies for three maneuvers are presented.
- A technique to objectively define the alignment reference point for step response maneuver is developed.
- Concept of metric validity window is introduced, and its application is demonstrated.
- A frequency domain analysis methodology for vehicle dynamics is proposed and its application is demonstrated.
- A methodology to assess the double lane change maneuver is introduced. The maneuver is investigated in two parts. Methodology involves determining an objective definition on how to partition the data, and how to align it.
- Several weaknesses and the limits of validity of the simulation model are identified.

5 Discussion and Conclusion

In this chapter, the results of the thesis are presented, transferability of the results is discussed and possible future work are suggested.

5.1 Results

In this thesis a validation methodology for vehicle dynamics simulation models and its application is presented.

The developed validation paradigm has a top-down approach to the problem. First, the term “validation” is explored and defined. It is established that a simulation model can never be absolutely valid, since a simulation is only an imitation of the reality, but can only be “not invalid”. According to this axiom, it is concluded that a simulation model’s validity is dependent on the application for which it is aimed.

Next, it is ascertained that vehicle dynamics simulation models can only be validated using test maneuvers although they are aimed for real life maneuvers. Consequently the target real life events should be analyzed in terms of requirements and simulation targets should be determined.

According to these requirements, a group of test maneuvers which reveal the dynamic characteristics of the vehicle and exhibit similar characteristics to those of the real event should be selected at the start of the model development project. The selected maneuvers should separately be analyzed, objective techniques to handle the data be explicitly defined and validation metrics and criteria be declared.

The experimental data and simulation data are handled according to these guidelines, and the results are compared according to the defined validity criteria. If the simulation results and metrics satisfy the criteria, then the simulation is deemed to be “not invalid” and is corroborated to be used in the planned task.

If the simulation model fails to meet one or more of the defined criteria, the model is deemed invalid, and model iteration should be performed. The results are analyzed to determine if the results indicate a modeling error or a modeling inadequacy; and if a conditional validity in terms of system variables can be defined.

Three test cases are presented to demonstrate the application of the paradigm. Each maneuver is separately handled, data analysis methodologies are explained, metrics and accuracy criteria are defined, implemented and results are presented. New definitions and calculation techniques for reference points, such as the alignment point for the step response maneuver, or the partitioning point for the double lane change maneuver are introduced, which can help automating the assessment procedure.

The developed methodology successfully identified the shortcomings of the tested simulation model, and defined the limits of application. Several insights for the deficiencies of the model are reported in the analysis but the iteration step of the methodology is not demonstrated.

All in all, the approach offers a step-by-step procedural methodology for the simulation engineer. Utilizing the proposed methodology will help to achieve more time and cost efficient simulation projects with increased model confidence by enhancing the traceability of the validation process.

5.2 Transferability of the Results

The developed approach to validation question is demonstrated using a non-linear double track model of a compact class vehicle to be used in the student tutorials.

If the model was aimed for a different application, the accuracy requirements or test maneuvers might have been different. However the logic behind the selection of these parameters would remain the same. Additionally, only the global response quantities were analyzed in this work. The same principles do apply to the system variables that were not measured or considered.

The simulation model properties also do not affect the transferability of the results. A multi body vehicle model with more model depth or a single track model for linear analysis would benefit from this approach in the same way. It must be noted that, in the case of a multi body model, modal analysis is a powerful tool to validate the entities of the system separately. Type of the vehicle is also irrelevant and simulation model of any passenger car, or motorcycle, or commercial vehicle can be assessed using the presented methodology.

Although the paradigm is aimed for vehicle lateral dynamics simulation models; same principles can be extended to longitudinal and vertical dynamics. As a matter of fact, it is possible to conclude that any simulation model for a system (a ground vehicle or not) with measurable time histories and dynamical response can benefit from such an approach.

5.3 Future Work

There are several interesting follow up research subjects to pursue. Of the tested maneuvers, double lane change maneuver is a closed loop maneuver with the driver as the sensor element receiving the visual feedback from the test track, the controller element calculating the required corrections, and the actuator element applying the control input to the steering wheel. However, the simulation model used the steering wheel angle measurement from the experiments as the input source, effectively creating an open loop system. It has been hypothesized that in such cases, implementing a driver model can have certain advantages in assessing the simulation model's credibility, revealing certain new aspects which are open to new readings.[156]

Another interesting subject that needs further research is a comparative assessment of sine sweep and steering wheel impulse maneuvers to determine their advantages and disadvantages in experimentation and analysis of the frequency domain response of the vehicles.

It has also been established that frequency analysis of subsystems is a sound technique to detect inadequate modeling instances.[157] A methodology to systematically test the subsystems of a multibody model in the frequency domain can help enhancing the credibility of such models.

In this work, the experimental uncertainties are estimated to define the EDZ which is used as a reference corridor for the simulation data. On the other hand, calculated uncertainties could have been propagated into the simulation model. Approaches using these techniques consider such model conditioning an essential part of the validation efforts.[158]

Finally, methods which involve numerical topologic comparison of the experiments and simulation have not yet been applied to validation of vehicle dynamics simulation models. Such techniques have the potential to summarize many important characteristics of the validation assessment procedures to one metric.[159]

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