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Validation of vehicle dynamics simulation models – a review

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In this work, a literature survey on the validation of vehicle dynamics simulation models is presented. Estimating the dynamic responses of existing or proposed vehicles has a wide array of applications in the development of vehicle technologies, e.g. active suspensions, controller design, driver assistance systems, etc. 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 report presents different views on the definition of validation, and its usage in vehicle dynamics simulation models.

Keywords: validation; simulation; modelling; vehicle dynamics

1. Introduction

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.

Validation of vehicle dynamics simulations is an intersection of two fields of study: simulation of vehicle dynamics and validation of simulations. Thus, the literature domain can be divided into three main subjects: verification and validation (V&V) of computational models; validation of vehicle dynamics simulation models in practice and validation methodologies for vehicle dynamics simulation models.

In this paper, first the literature on V&V of computational models is presented. Definitions of the V&V concepts, and approaches to the question from different disciplines are explored. Next vehicle dynamics and the utilisation 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.

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2. V&V of computational models

2.1. *Definitions of concepts of V&V*

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.[1] The process of verifying and validating a model should also lead to improving a model's credibility with users [2] and decision-makers.[3]

Verification of a simulation model, in layman's terms, is defined as 'building the model right'. According to Carson,[1] verification is the techniques that are used to assure that the model is correct and matches any agreed upon specifications and assumptions. Another similar definition is the process of determining if a computational 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.[3] In the field of computational fluid dynamics (CFD), the American Institute of Aeronautics and Astronautics (AIAA) definition 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.[4] In another source concerning CFD applications,[5] verification is defined as a process for assessing simulation numerical uncertainty and estimating the sign, magnitude and uncertainty of the simulation numerical error.

Same richness of definitions can also be encountered for the validation concept. Similar to verification, in layman's terms, validation means 'Building the right model'. One of the earliest definitions is the process of confirming that the conceptual model is applicable or useful by demonstrating an adequate correspondence between the computational results and the actual other theoretical data.[6] Validation can be defined as the 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.[1] Validation is the substantiation that a computerised model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model.[7] It is the process of determining if a mathematical model of a physical event represents the actual physical event with sufficient accuracy.[3] According to AIAA,[4] 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.

Absolute validity is refuted by many experts.[2,3,8,9] 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.[8] 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 modelled and the simulation results.

2.2. *Philosophical aspect*

The main question of concern is 'Can a simulation model be validated?' when the philosophical perspectives to the simulation and validation are considered. This question is actually very similar to one of the main problems of philosophy of science, regarding the scientific progression.

As previously stated, pure and absolute validation is impossible. According to Popper,[10] scientific theories cannot be proven; they can only be tested through observations. Therefore, a simulation model can only be invalidated when the performance of the model fails to meet the accuracy criteria, but cannot be validated otherwise. If the simulation model fulfils the defined validity criteria, then it can be deemed 'not invalid' under the defined specific set of operating conditions and limits.

Comparison of different perspectives on philosophical aspects of validation is examined by Klein and Herskovitz.[11]

2.3. *Approaches to V&V*

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 [1] provides a simple framework for validation of production plant simulation models by introducing practical techniques and guidelines, and categorisation of modelling errors. The presented framework can be summarised 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 with the reference results.

Another approach to the subject is to use the conserved quantities throughout the system during specific times or modes of operation for validation purposes.[12] This method analyses models to understand how conserved quantities (momentum, heat, kinetic energy, etc.) flow through the model and these quantities are properly conserved.

Sargent, 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.[2] 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. According to Sargent, a model should be developed for a specific purpose (or application) and its validity should be determined with respect to that purpose. A model is considered valid for a set of experimental conditions if the model's accuracy is within its acceptable range and the accuracy requirement should be defined at the start of the development project. However, even if a model passes every experimental scenario satisfactorily, 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, subjective decision of the model user (customer), independent V&V where a third party runs the V&V work, and scoring where subjectively determined scores for various aspects of the simulation model's performance are assigned.

A similar scoring approach to increase the credibility of simulation models is developed by National Aeronautics and Space Administration (NASA).[13] The approach categorises V&V stages and assesses the exerted effort according to a rigour scale for each of the categories. This creates an easy to handle overview of the V&V work for the decision-makers.

Oberkampf and Barone [14] attempted to devise a methodology to construct validation metrics. 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, and should exclude any indications of the level of adequacy in agreement between the simulation and the reality (such as 'good', 'excellent' or 'poor').

For the V&V of simulation models, seven rules for model selection and implementation are proposed by Babuska and Oden [3] for finite element simulation models. This approach attacks the root of the validation problem, by first selecting an appropriate, well-proposed 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 independent of the validation. 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 V&V and approaches the problem from a cost-risk analysis aspect.[9] Here, 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, acknowledging 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 analysed depending on the application. Also, it has been noted during V&V analysis, that it is better to use more than one method simultaneously instead of using one optimal method, since every method has weaknesses and such a practice will remedy these and increase the model credibility.[15]

In a study by Sarin et al.,[16] a methodology to construct a metric which is used to compare time histories that are outputs of simulation models with time histories from experimental tests with emphasis on vehicle safety applications is established. The constructed metric incorporates phase, magnitude and topology features in order to quantify the error between the simulation and the experiment. Also a regression-based validation model was proposed which uses this newly developed metric in order to reproduce the subjective judgements of subject matter experts.

Romero worked on propagating system uncertainties into the simulation model through model and data conditioning [17] and considers these as an essential step in model validation.[18] 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. 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 in order to create an augmented or conditioned model that yields total simulation uncertainty that is compatible with the uncertainty of the conditioned experimental data was proposed.

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 which uses Bayesian hypothesis testing and a quantitative multivariate validation method based on probabilistic principal component analysis [19] and multivariate Bayesian hypothesis testing are proposed for simulation models of dynamic systems.[20] These works focus on computer-aided engineering models of automotive safety applications (crash simulation and dummy passenger models), but have the potential to find usage in vehicle dynamics as well. Using reversed hypothesis testing to validate methods [21] and employing statistical hypothesis testing as a form of objective cost-risk analysis for validation of simulation models [22] 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 modelling practice, is deemed more critical, since accepting an invalid model as valid will result in the 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 minimising it. Type I error (false positive) 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.

3. Validation and vehicle dynamics simulation models

3.1. *Vehicle dynamics and modelling*

The theory of vehicle dynamics is well established and in this section different sources for vehicle dynamics and simulation are named.

The earliest and simplest vehicle dynamics model is the single track model.[23] It is still in use today [24] and it can be traced back to 1940.[25] Fundamentals of modern understanding of vehicle dynamics and the description of many important characteristics, such as understeer are presented by Olley [26]. One of the first vehicle models was proposed by Segel [27] for the time domain analysis, and frequency domain response was explored subsequently in the 1970s by McRuer and Klein.[28]

With the emergence of electronic brake systems 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 and fast application) and financial benefits [29] (reduction of experiment, measurement and prototype costs, early fault detection especially in the cases when the software of more than one components interacts, better optimisation interface and faster development cycles).

Many textbooks can be found in the literature which explain the fundamentals [30] and advanced applications of different aspects of vehicle dynamics such as tyre and brake dynamics,[23] engine and powertrain management [31] and modelling of vehicle dynamics.[29,32] Lugner and Plöchl's work provides an overview of simulation of vehicle dynamics and model types.[33]

One of the main utilisation fields of vehicle dynamics simulations is driving simulators. Driving simulators must not only model the dynamics of the vehicle accurately, but also they must provide correct sensory feedback to the driver. An extensive state of the art survey on vehicle simulators by Blana can be found in the literature.[34] Another study by Allen et al. also provides insight on the prospects of the simulator technologies.[35]

Requirements for vehicle dynamics simulation models are explored by Allen and Rosenthal.[36] 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 emphasises the importance of an accurate tyre model with appropriate depth for the application, since main phenomenon causing the dynamics of vehicles, occur between the tyre and the road surface. Tyre modelling is a fundamental aspect of vehicle handling dynamics and in order to capture the full range of vehicle stability characteristics, tyre 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 tyre model which excludes roll steer, deflection steer due to compliance and inaccurately calculates individual slip angles of the tyres.[37] A survey on the modelling applications of the interaction between the tyre tread-block and the road surface is provided by Wallaschek and Wies.[38]

This importance is further explored in another study with comparisons of tyre models with different model depths.[39] The effects of different 'legal' tyres on the same vehicle using fishhook and sine-with-dwell manoeuvres are demonstrated by Arndt et al.[40] Up to 33% discrepancy is observed for lateral acceleration gain between two approved tyres of the same manufacturer.

One of the most importance sources on tyre dynamics is written by Pacejka,[41] who also developed the so-called Magic Formula, an empirical tyre model which relies on curve fitting using experimentally measured tyre data. Rill [42] developed a first order analytical tyre model based on Taylor expansion of governing differential equations and another model based on mechanical analogies is proposed by Lacombe.[43] Analytical models which use modal parameters are also present.[44] Physical models, which use finite element model to simulate the mechanics of the tyre 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.[45] Hybrid tyre models combine different model types to exploit their advantages. A compromise between finite element models and analytical models which is based on the macroscopic physical description of tyres is proposed by Gallrein and Bäcker.[46] Similarly analytical-empirical hybrid formulations are also existent.[47] Guo and Lu have developed a semi-physical model, where a detailed nonlinear analytical description of tyre characteristics is supported with experimentally measured tyre parameters with satisfactory results.[48] The modelling of tyre wear is also an important aspect. Tyre wear is a major error source in experimentation. Such models have uses in race performance prediction, tyre development and fleet management.[49]

3.2. *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 an individual case, like vertical dynamics of articulated vehicles [50] or lateral dynamics of light vehicles.[51] 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. [52] and Heydinger et al. [53] worked intensively on development, parameter measurement and validation of vehicle simulation models. A multibody full vehicle model is developed, parameters for spring, damper, tyre and roll characteristics are measured and 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, and comparison of simulation predictions with field data using the same driver control inputs. The importance of independent parameter measurement is emphasised. 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 responses and nonlinear effects; and in frequency domain to check the high-frequency dynamics during transient manoeuvres.

The manoeuvres 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 manoeuvre (lane change in this case) are performed. 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 emphasising 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 multibody vehicle model for ride analysis is demonstrated in a project by Alasty and Ramezani [54] In this work, the reference data are obtained using a more complicated multibody model. No metrics or statistical analysis is utilised 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.,[55] a heavy truck simulation model is first modified according to comparison of experimental and simulation results for lateral steady state manoeuvres; and then validated for dynamic response using a transient manoeuvre. 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 diminish the credibility of the validation judgement. Also, no metrics or statistical analysis is 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 manoeuvre. 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.

Wade-Allen et al. discuss the validation of a full vehicle model in their 2002 paper.[56] The research 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 tyre saturation, the parameter measurements of the subsystems of the simulation model must be accordingly measured, such as the tyre data over large slip conditions and higher than normal load, and other nonlinearities due to larger deflections caused by the highly dynamical manoeuvres.

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 manoeuvres, 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 manoeuvres. 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 overlaid time histories of test and simulation results.

This work reflects a correct approach to the validation problem, but with several shortcomings. The importance of parameter estimation and data validity is well emphasised, and the sequencing of test manoeuvres, from steady state to transient and to real-life imitating manoeuvres is proper. An alternative manoeuvre 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. [57] 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 the dynamical testing through linear swept steering manoeuvre and fishhook manoeuvre, 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 are 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 manoeuvres used in validation of the system's response is not explicit, and the assessment criteria are vague. Neither validation metrics nor confidence intervals are constructed.

Another study by Hu [58] 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.[53,59] In this study no validation metrics or statistical analysis is 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 analysed 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 optimisation exercise is presented by Cassara et al.[60] Because of the large number of degrees of freedom and tuneable parameters of the targeted simulation model, which is a Tractor-Semitrailer model for ride and handling analysis, such an approach is proposed. To address this complicated question, modal analysis is performed first at the component level and then at the subsystem level and then the frequency response of the vehicle system is inspected. Manoeuvre odometrics are checked as well, and several ride-related components are analysed in the frequency domain. Focus of the research lies on the subsystem interaction and the effect of frequency response modelling accuracy of subcomponents to the total system response considering ride and handling. No criteria are used to quantise 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 armed forces, called Model Post Processor is developed by Howe et al.[61] 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 kinematics, compliance, etc.) is performed by a consistency check subroutine, and dynamic metrics are checked by another subroutine through a range of test manoeuvres. Dynamics manoeuvre range encompasses fundamental tests for longitudinal, lateral and vertical dynamics.

Horiuchi et al. have proposed a model-based validation procedure which evaluates the control and intervention performance for the certification of advanced chassis control systems.[62]

The proposed validation procedure handled the evaluation of the static and dynamic properties in two consecutive steps. Braking stability is treated as a static property and is evaluated by constrained bifurcation and continuation method, whereas the dynamical characteristics of the vehicle are evaluated by the optimisation-based worst case scenario method. This work is a good demonstration of application modelling and validation techniques to advanced chassis control systems and virtual testing.

3.3. *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 [63] 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. [59] 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 emphasises 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. [64] carries on this approach and reapproves the conclusion that a complete validation analysis should be performed in time and frequency domains. In this work, six manoeuvre classes are identified and tested. Five of these are identified to be the primary validation manoeuvres. These are steady state lateral performance (low-frequency cornering), transient lateral performance (manoeuvres 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 manoeuvres (suspension kinematics and ride dynamics). The sixth group of manoeuvres, designated as 'other manoeuvres' that attempt to imitate real-life situations (double lane change, fishhook, etc.) are not considered among the primary validation manoeuvres. Contrary to the preceding study,[59] no validation metrics or accuracy criteria are used in this work.

Another approach to the problem is suggested by Bernard and Clover.[65] Three questions are stated to define the validation of a model:

- *Conceptual validity*: Is the model appropriate for the vehicle and manoeuvre 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 modelling 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 manoeuvres 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 manoeuvres and manoeuvres with tyre saturation (limit handling), checking the tyre forces as a function of kinematics and normal load is advised. This helps detecting the errors in tyre model and suspension kinematics.

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

This work criticises Heydinger et al. [59] for not only increasing confidence in the model, but also accepting errors as long as the scatter is in an acceptable range, which would mask the errors that stay within the defined interval. This view is supported with an example case: an incorrect centre 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 manoeuvre in which the lateral load transfer plays a significant role is the target of the simulation project, such as fishhook manoeuvre, centre 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 be directed to not the last stage of the validation procedure, but to the planning stage, where the target manoeuvre is analysed and test manoeuvres and validation metrics are chosen.

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,[65] the most dangerous part in data entry of parameter values is tyre and suspension data. Both the tyre model and the suspension model have many parameters, and this step is prone to human error.

In a follow-up study by Gruening and Bernard,[66] data validity and faulty data entry problem 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 pre-processing procedure is suggested. Running the simulation through a recipe of manoeuvres 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 manoeuvres.

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, there would be more than one likely cause, for example one of the parameters associated with tyre 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 tyres 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 manoeuvre (e.g. steady state cornering), individual load or force measurements for the tyres, or an isolated test case would be more practical. In the first two of these suggestions, there is absolutely no guarantee that the simultaneously erroneously entered (or measured) parameters can be identified. Concerning the third suggestion, generally speaking, it is impossible to devise a manoeuvre 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 manoeuvres (for example lateral and longitudinal manoeuvres 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. [67] 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 behaviour, and a valid model according to analysis of general system response does not guarantee valid subsystems models.

The presented validation method is summarised 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 behaviour 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 manoeuvre, are chosen. The research does not offer a 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. [59] and Garrott et al. [64] focus on operational validity and comparison of test measurements and simulation results; Bernard and Clover [65] and Gruening and Bernard [66] recommend analytical solutions and face validity checks for validation and vehicle tests only for parameter identification and error hunt; and Allen et al. [67] emphasise importance of face validity, analytical solutions and common sense checks with less methodical approach to vehicle testing. A summary of these studies is presented in Table 1.

Table 1. Summary of the included model validation studies.

Reference	Aim of the model	Method
Salaani et al. [52]	Handling	Independent parameter measurement and real reference data Steady state, transient, frequency and real life like manoeuvres Analysis in time and frequency domains Confidence intervals and no validation metrics
Heydinger et al. [53]	Handling	Independent parameter measurement and real reference data Steady state, step, frequency and real life like manoeuvres Analysis in time and frequency domains Confidence intervals and no validation metrics
Alasty and Ramezani [54]	Ride	Reference data from a more complicated model Analysis in time domain No statistical analysis and no validation metrics
Mcnaull et al. [55]	Handling	Model correction using experimental data Transient manoeuvres Analysis in time domain No statistical analysis and no validation metrics
Wade-Allen et al. [56]	Handling	Parameter measurements at targeted operating regime Steady state and transient manoeuvres Analysis in time and frequency domains No statistical analysis and no validation metrics
Ozan et al. [57]	Handling	Independent parameter measurement and real reference data Transient manoeuvres Analysis in time domain No statistical analysis and no validation metrics
Hu [58]	Ride	Model correction using experimental data Analysis in time domain No statistical analysis and no validation metrics
Cassara et al. [60]	Ride and handling	Modal analysis at subsystem level Analysis in frequency domain No statistical analysis and no validation metrics
Heydinger et al. [59]	Handling	Independent parameter measurement and real reference data Steady state, transient, frequency and real life like manoeuvres Analysis in time and frequency domains Statistical analysis and validation metrics
Garrott et al. [64]	Longitudinal, handling and ride	Manoeuvre classification Analysis in time and frequency domains No statistical analysis and no validation metrics
Bernard and Clover [65]	Handling	Data validity and data entry errors No manoeuvre selection Analysis in time domain No statistical analysis and no validation metrics
Allen et al. [67]	Handling	Data validity and data entry errors Steady state, transient and real life like manoeuvres Analysis in time domain No statistical analysis and no validation metrics

4. Conclusion

In this work, a literature survey on approaches to validation of vehicle dynamics simulation models is presented. Several studies on validation and verification theory are discussed and general approaches to the validation problem from other fields of engineering are examined.

Simulation and validation practices and methodologies in the field of vehicle dynamics are presented.

There are many and similar definitions for V&V 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 specific requirements and limitations of the application.

Existent works on validation methodologies for vehicle dynamics simulations focus on different aspects of the question. Neither there is a standard in experimentation and data handling processes in vehicle dynamics modelling, nor is there a standard reasoning process in the vehicle dynamics modelling 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 recognisable pattern and their contents and structures 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.

A vehicle model should be analysed in time and frequency domain using both steady state and transient manoeuvres. Both analyses can show characteristics which may go undetected if only one is used. There are basic manoeuvres which demonstrate the general dynamics of the vehicle, and then, there are 'other' manoeuvres, which imitate real-life scenarios.

The validation criteria are dependent on the application; the validity metrics and the data handling are dependent on the chosen manoeuvres and analysis; and the manoeuvre selection is dependent on the targeted real-life phenomena to be simulated. Thus, validation of a vehicle dynamics simulation model should be planned according to the characteristics of the real-life phenomena it is trying to reproduce. The test manoeuvres to be used in the validation should be determined early in the project timeline and according to the analysis of the real event to be simulated.

To this aim a validation recipe, so to say, which incorporates a top-down approach is required. Real-world manoeuvres and test manoeuvres need to be analysed, and the relationship in between needs to be examined. For each test manoeuvre, experimental procedures, data handling techniques, validation metrics and accuracy criteria should be explicitly declared in the project documentation. Such an approach will help to achieve more time and cost efficient simulation projects with increased model confidence by enhancing the traceability of the validation process.

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