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A METHOD FOR MODELING AND SIMULATION OF JOINT DRIVER-VEHICLE PERFORMANCE AT HANDLING LIMITS

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Abstract

In order to be competitive on the Market, the Automotive Industry demand time and cost cuttings. This demand exists parallel to a Market call for improved Safety as well as Cars equipped with new advanced technology. An extended use of methods for Modeling and Simulation has become increasingly important in meeting both Corporate and Market desires. Systems for Vehicle Dynamic Control (VDC) are debated and performance monitoring is requested. This paper focuses on computer-aided engineering (CAE) and the development of novel control concepts for Vehicle control and stabilization. The main contribution of this study is the creation of a test method suited for the Axiomatic Design (AD) method in deriving the Vehicle Handling Characteristics. The Driver's Need of Control and Vehicle behavior is studied in a joint performance perspective. The Driver's partial loss of control and recovery is modeled and applied. Driver recovery is studied in a Car skidding scenario. Finally, the result from the validation of the test method is presented, the test in which six drivers in a Motion-based Driving Simulator have been used.

Keywords: Engineering Analysis, Man-Machine Interaction, Axiomatic Design, Design–for–X

1. Introduction

Studying a method for Modeling and Simulation of joint Driver-Vehicle performance at Vehicle handling limits is encouraged by demand for improved Safety and corporate profitability in the Automotive industry. Together with a both faster and cheaper development process, a higher level of quality, safety and functionality is expected from a Customer perspective. This leads towards demands for improved competence for Modeling and Simulation in Engineering and Testing of new systems in the Vehicle Development Process (VDP). Recently, the European Commission has enlightened the experience from a couple of years use of Vehicle Dynamic Control (VDC) systems in Cars and its performance on the Roads. Monitoring of the potential benefit from preventing loss of control is recommended in developing new concepts for vehicle stability and control [1]. These systems are based on the anti-lock braking systems (ABS) technology aimed for improved safety and comfort but in some critical driving situations the value of a VDC system can be questioned [2]. The problem with a Driver modified behavior during braking or stabilization seems to be unsolved. For example, the Driver wants to stop the Vehicle promptly and the ABS system searches for conditions where the wheels are not locked up allowing braking and simultaneous steering [3]. A driver modified behavior is suggested to be accounted for while specifying Vehicle Handling Characteristics.

For testing of Handling Characteristics, Prototype Vehicles and Test Drivers are commonly used for verification of target fulfillment. In the future, the prediction of Handling Characteristics is supposed to be used by Modeling and Simulation, substituting Prototypes and Drivers. Driver modeling is supposed to be the key problem in specifying the desired Vehicle characteristics and improved methods for both verification and validation of target values will be needed.

By use of Systems Engineering (SE) principles and Modeling and Simulation (M&S) methods in combination with an Axiomatic Design method, a better and earlier understanding of Driver needs and performance at handling limits is assumed to be possible. Late studies on Pilot Induced Oscillation (PIO) or unwanted Aircraft Pilot Couplings (APC) indicate that poor Vehicle responses in many cases trigger unwanted oscillations [4]. For that purpose, a method for avoiding unforeseen Vehicle characteristics based on a poor specification of Handling Characteristics methods is suggested to be developed and tested.

In this paper, a method for Modeling of a Driver behavior at Vehicle Handling limits is presented. This method is aimed at supporting a Chassis Engineers' specification, engineering and testing of Vehicle Handling Characteristics and Computer Aided Engineering (CAE) widely used for a Vehicle Dynamics analysis of Handling Characteristics. In present standardized ISO tests, it seems that tests of Drivers' partial loss of control and recovery are not used or modeled. A joint Vehicle assembly approach with real Drivers is used as a base for Performance modeling and prediction. In the subsequent sections, the VDP is visited and used as a frame for the study. The Axiomatic Design method is then discussed and used as a base for the presented M&S approaches. The structuring of requirements and methods for testing is emphasized. An alternative use of available Driver Models in Vehicle Dynamics simulations is discussed briefly. A test method is then developed for both modeling purposes and for establishing a Driver's Control Need. Finally, the test method is validated using real Drivers and a Vehicle Model in a motion-based Driving simulator. Testing of the method applicability in a fixed-base Driving simulator together with a Hardware in the Loop (HIL) simulation tool is reported.

2. The Vehicle development Process

The main concern in this section is how the Engineering activities for Specification, Engineering and Testing can be supported in defining Vehicle Handling Characteristics. The VDP is briefly sketched as a framework for the method application. The new Car model development starts with Market analysis and Styling suggestions and ends up in a Design freeze before the Start of Production (see figure 1). The process is serial and has given way for concurrent engineering [5]. One common problem in the present VDP is the flow and availability of Engineering Information which is needed at early stages.

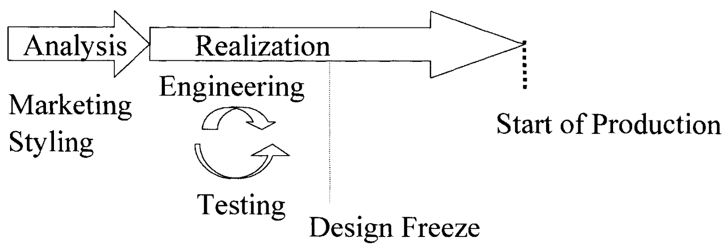

Figure 1. Engineering and Testing in the Vehicle Development Process

The method discussed in this study focuses on improvements that can be made in Chassis Engineering and Testing concurrent and in close cooperation with the Market analysis and specification activities. A new system for Vehicle Control is almost in all cases a Commercial of-the-shelf (COTS) product that shall be integrated into an existing Car concept. Nevertheless, the functional requirements have to be developed in a complete car setting. The main question addressed is what information will be needed and where to find it when designing excellent Handling Characteristics. From a Systems Engineering perspective, technology is introduced Bottom-up and requirements and needs approaching Top-down [6]. The concern here is how top-down and bottom-up processes are balanced for optimal Product performance. In the following part an Axiomatic Design (AD) method is introduced which exhibits top-down decomposition of requirements and mapping of Customer and Functional domain capabilities.

2.1 Design Methodology

AD is selected for being the key method capturing Customer/Driver Needs (CN) simultaneously with a Functional Requirements (FR) derivation when designing desired and successful products. A design activity is generally started by input from Marketing with experiences from previous product developments. These specifications are in general vague and cannot easily be translated into Engineering terms [7]. The author claims that these specifications are often a mix of Customer Need, Components specification, Constrains or Production Variables. AD uses a four domain concept representing Customer Attribute/Needs (CA), Function Requirements (FR), Design Parameters (DP), and Process Variables (PV) that a designer is requested to take into consideration when creating design proposals (see figure 2). In addition, Constrains are used giving the bounds of an acceptable solution. They are of two kinds, Input Constrains are imposed as part of the design specifications and System Constrains are imposed by the System in which the design solution has to function.

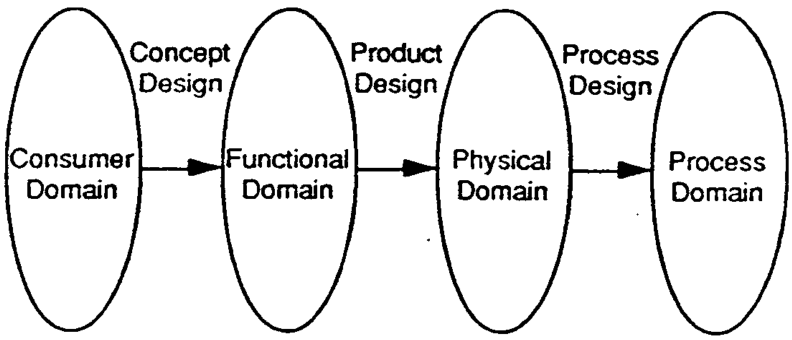

Figure 2. The Concept of Domains in Axiomatic Design [7]

A design decision which is made during the mapping process is supported by two Axioms.

Axiom 1: The Independence Axiom, *Maintain the independence of the Functional Requirements* (FRs).

Axiom 2: The Information Axiom represents the degree of robustness in the design. Although this is of interest for this application, it is left for further study.

In the following, only Axiom 1 is discussed. This is because the study is focused on a method supporting Chassis Engineers in maintaining independent FRs, which lead towards good design.

For example, the following information is assumed to be easily found and structured, based on global or corporate knowledge on Safety and Driving:

System Constrains: The driver is responsible for driving the Vehicle and for interactions in the Traffic Environment.

Input Constrains: Handles well and safely in all driving conditions

FR1 Provide Vehicle Stability	**PD** Design for Stability
FR2 Provide Driver Authority	**DP** Design for Driver Authority
FR3 Provide Driver Variability	**DP** Design for Variability

To solve this problem it is assumed that Driver Needs must be exploited when examining Functional dependencies.

3. A method for establishing Driver Needs

The endeavors to understand and specify the requirements originating from Driver needs are supposed to be made easier by use of a CAE tool and a dynamic Driver model. A worst-case scenario is proposed to be modeled covering Drivers partial or full loss of control at or near handling limits. Important factors that are being considered are Driver Characteristics, Vehicle Handling Characteristics and Vehicle Transient Response Characteristics in combination with Road conditions [8]. The author argues that there is always a lag in Vehicle responses, big or small, and it must therefore be encountered in the design of Vehicle stability. The critical point in establishing basic needs is assumed to be the Driver Model quality needed for real time interaction. A Driver Model suited for the assessment of Driver Control Needs is considered to be exhibiting dynamic performance properties.

3.1 Driver Modeling

From a literature survey on recent Driver Modeling approaches, the following is found, however, not covering all. In brief, most literature on the topic may be grouped into three categories: 1. Development of onboard Controllers aimed for Active Safety Systems development, 2. Support of Engineers prediction of Vehicle Dynamics, and 3. Research on Driver behaviors in a Traffic Safety context. Many of the existing models rely on a Control Theory base portraying a Driver input/output function in an Information processing context. The Hybrid Driver Model is a good example of late modeling approaches that can be used for simulation of Vehicle motion and driving [9]. It is claimed that this model realistically reproduces the behaviors of different Driver types with mental workload considered too. A commercial product is also selected representing models that can be used together with commonly used Vehicle Dynamics Simulation tools. The IPG-Driver together with ADAMS are typical commercial products available on the market. The IPG-Driver is built on training of the model executing maneuvers that seems to be complicated. The underlying mechanisms used for IPG-Driver Modeling are not obvious [10]. In this study, the actual Driver behavior, while losing control, is suggested to be modeled together with a well-recognized Vehicle model in a drastically changed Road condition. The joint real time interaction and modification of behaviors is of paramount importance in assessing Vehicle Handling Characteristics at physical limits [11]. The test of performance at handling limits is therefore assumed to be the first step towards the understanding of Driver Needs as a base for further Modeling. An alternative approach is joint Modeling by use of experiments in simulators with a Systems Identification technique often used for controller development [12]. However, the non-linear nature of the system does make this approach less straightforward here.

3.2 Test method development

The method development is supposed to be made for evaluation of design proposals from an AD perspective. Systems Engineering principles are suggested for defining the evaluated system. The proposed activities are Integration of Driver and Evaluation of Performance in a simulator experiment. But for evaluation purposes, a step for Identification is developed. This additional Identification step is made because Driver-Vehicle limits must be identified before an Evaluation of Performance can be made.

Step 1 Integration of Driver in the Loop

In this step, a real Driver is integrated using a motion-based Driving simulator together with a recognized Vehicle Model and a Road Model forming a joint system for driving purposes. This, since a closed-loop control configuration is required in the experiment for limit identification.

Step 2 Identification of limits

In this step, an experiment is designed for Joint Handling Limits detection. This is the most critical step where experimental treatment and a test situation has to be defined. Lessons learned from Aviation are here used for the definition of a test situation. Pilots' modified behaviors are due to a stalling Aircraft where a Flight Control System is naturally slow in response. Vehicle response to Driver input is modified portraying a stabilization process that is performed due to abrupt and sever changes in the Road condition. Modification of the Vehicle response is made by a delayed control signal from the Steering wheel. The delayed control signal is then varied in order to avoid training effects. The considered test condition is a skidding Car that is, from the Driver perspective, unexpectedly forced into skidding. A pre-test of the experiment is then performed for test of realism and treatment effects. A Vehicle response delay in the region of 80-160 milliseconds is assumed to be used when starting the experimentations.

Step 3 Evaluation of Performance

To start with, the Driver is practicing for familiarization with the undisturbed Vehicle Characteristics in the Driving simulator. After the Driver has practiced recovery from skidding 20 times without any delayed vehicle response, the test is started. An acceptable performance is mainly defined by measuring of lateral displacement, steering wheel angle and time to recovery, reflecting real life safety requirements. A completed recovery is when the Vehicle is stopped from skidding in the expected lane without swerving over several lanes.

4. Validation of Test Method

The developed method is validated by using Real Drivers, Driving Simulators and a Hardware in the Loop (HIL) simulation tool. In a recent Research report the test method is validated and tested for the applicability of collected data [13]. Tests are performed where data from Simulator experiments, together with a Systems Identification tool, are used for a Driver Transfer Function development in HOPSAN, a Hardware in the Loop tool developed at Linköpings Universitet [14]. Finally, the method is tested in V-SIM (a fixed-base Driving

Simulator developed at Linköpings Universitet) connected to HOPSAN where the method for delaying the signal to the Vehicle Model is tested with a good result.

4.1 Driving Simulator experiment

Method

Subject

Six male subjects participated in this explorative study. The subjects were young drivers ranging from 26 to 33 years of age, with a mean age of 28,5. All subjects had a driving license and were experienced, meaning that they had had their driving license for at least 5 years, and that they had been driving at least 10,000 km a year.

Apparatus

The VTI driving simulator was used for the study. It is an advanced simulator that consists of a moving base system, a wide-angle visual system, a vibration-generating system, a sound system, and a temperature-regulating system [15]. These five subsystems can be controlled to operate in a way that gives the driver an impression of real driving.

Tasks

The road type presented to the subjects in the simulator was a two-lane, 7 m wide, rather straight, asphalt road. The road surface was characterized by low friction (coefficient of 0,4), corresponding to a Nordic winter road, and the visibility was similar to a cloudy winter day with visibility of approx. 400 m. The wind conditions were moderate to strong with wind gusts typical for the season. Two different routes, one for practice and one test route, were used in the experiment. The practice route was 20 km long, rather straight and easy to drive. The test route was 20 km long. It was also rather straight, and was not expected to cause the subjects any problem to follow or to remain on the road.

Vehicle

The car body used in the experiment was an ordinary mid-size passenger car equipped with automatic gearbox. The simulated physical environment in the ”car” corresponded to that in modern passenger cars. The Vehicle Dynamics Model that was used was developed and validated using a European Front Wheel Driven mid-size passenger car.

Vehicle response variation

The subjects were exposed to variations in Vehicle Control Responses during the experiment. For every recovery task a different time delay was applied to the Driver’s steering wheel input. The subjects were exposed to preprogrammed time delays grouped and ranging from original vehicle model value (no extra time delay) by increments to 160 milliseconds. The order of time delays was balanced within and between the subjects using no delay, 40, 80, 120, and 160 milliseconds delay due to the subjects steering wheel input..

Performance measures

Time to complete recovery was used as a measure when comparing the impact of different time delays on the subjects’ performance capability. It was defined as the time it took for the subjects to position the vehicle within a safe region of their roadside after the start of a skidding sequence. Time to complete recovery was sampled with a frequency of 50 Hz.

Lateral position, was measured in relation to a zero position, defined as the position where the central line of the road coincides with the central line through the driver's body. Lateral position was also measured with a sampling frequency of 50 Hz. Lateral position was measured continually.

Percent of successful Recoveries. The number of successful recoveries, compared to each experimental condition was analyzed in order to measure the subjects' performance when recovering from car skidding. The subjects were exposed to similar time delays four times.

Procedure

The subjects were randomly assigned to the preprogrammed blocks of delayed vehicle response conditions in the simulator and were given a written instruction describing their task. The subjects were told that they were supposed to drive a 20 km long route and that the car could start skidding at any time, due to changes in road and wind conditions. Their main task was to recover from car skidding and to continue their driving task. They were asked to drive in the way they normally drive a real car on a road with a legal speed limit of 70 km/h. They were also instructed to keep the maximum speed limit of 70 km/h all the time and, if necessary, as soon as possible prevent the car from skidding. While the subjects were driving, a short and abrupt repositioning of the rear end of the Vehicle was used for starting the skidding motion. This incident was simulated by giving an impression of abrupt crosswind onset. The direction of the crosswind onset was randomly changed, coming from either the left or the right side of the Vehicle. In each crosswind onset, a varied vehicle response was imposed. All subjects drove a 20 km long practice route before the test route. They practiced recovery from skidding 20 times without any manipulation of the vehicle dynamic characteristics, meaning no extra time delay in vehicle response. The practice route was used for familiarizing the subjects with the simulated Vehicle Characteristics and the main driving task.

4.2 Results

The results are based on complete data from six subjects. The following data is recorded and presented: Vehicle lateral displacement during recovery from skidding and Driver Steering Wheel angle during recovery, for analysis of the number of times the performing of complete recovery as well as the used time for completion of recovery.

Lateral position

It was predicted that the subjects should remain in the correct lane (right hand traffic) when Vehicle response delay did not exceeded 160 milliseconds. Figure 3 shows the plotted Steering Wheel angle for subject #3 (upper graph) and in the right lane (lower graph) depicting the trajectory for the lateral displacement of the Vehicle during recovery (from road centerline 0 to 3,5 meters). In Fig.3, the subjects' rapid counter steering and adjustment effort, due to left crosswind onset, can be compare to the values for delayed Vehicle response. No delayed response is used as reference value and is represented by a solid line, 80 milliseconds by a dashed line, 120 milliseconds by a dotted line and 160 milliseconds by a dash/dotted line. Note that the trajectories in the lower graph start from different points due to the Driver's selected positioning and headway in each test, that could not be counted for.

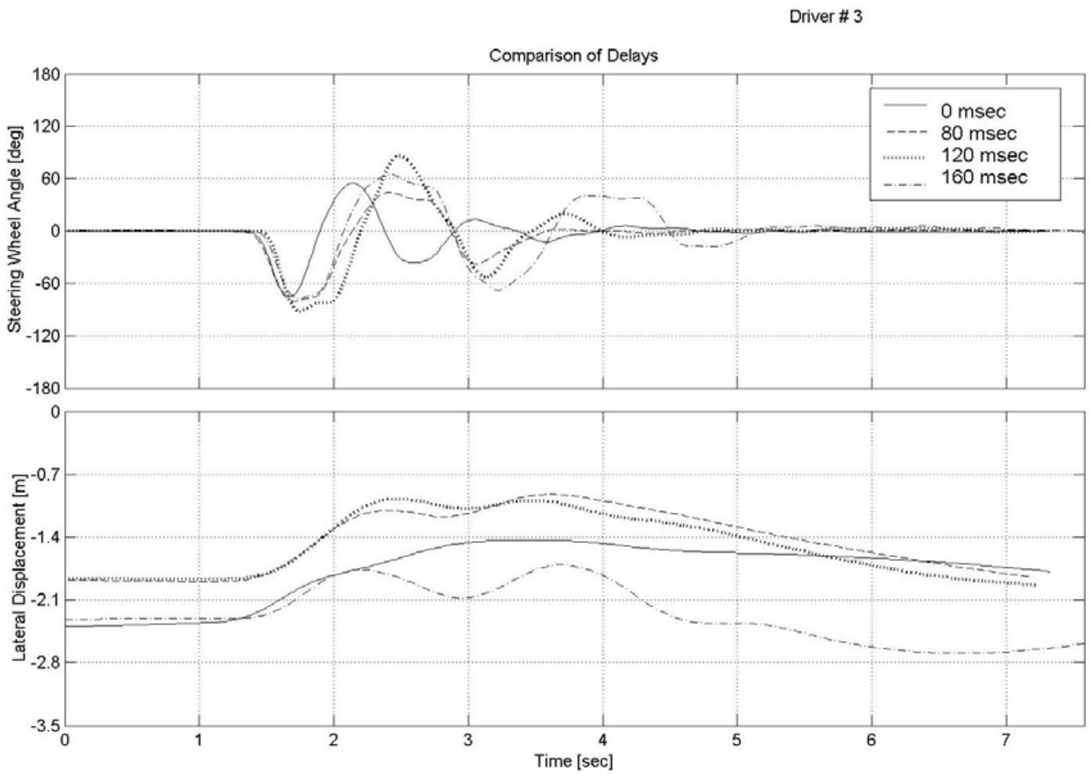

Figure 3. Comparison of Driver Steering Wheel angle and Vehicle lateral displacement

Percent of successful Recoveries

It was predicted that a subject should recover two times out of four in each condition. Figure 4. shows the relevant result from the fourth-time test in each condition. Since all subjects recovered four times out of four when exposed to no vehicle response delay at 40 milliseconds delay, those instances are rejected from the figures.

Time to complete recovery

It was predicted that the used time should not exceed 10-15 seconds when driving at a speed of 70 km/h. All subjects completed their successful recoveries in less than 10 seconds, Driver reaction time included. For calculation purposes, (thumb of rule) driver reaction time is claimed to be about 1 second as can be seen in Figure 3.

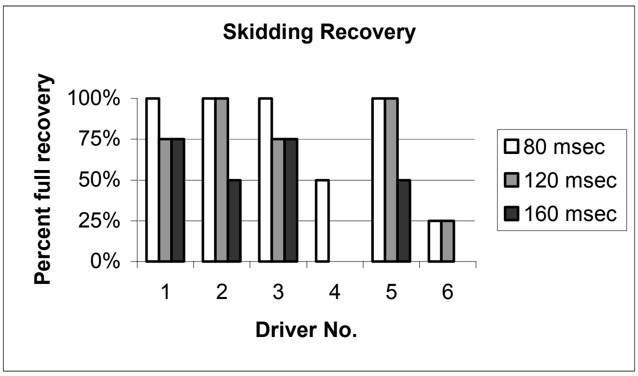

Figure 4. Result from 6 subjects four times in each condition test of recovery

5. Conclusion

The described method for Modeling and Simulation of joint Driver-Vehicle performance at handling limits is assumed to contribute to Road Traffic Safety. The test method for early understanding of Driver Needs related to the Functional requirements at Vehicle Handling limits is assumed to be well demonstrated. Establishing of Handling limits is supposed to be done by use of a Car skidding condition, while manipulation of the Vehicle Dynamics is used during recovery. The Driver Modeling approach and the test method used may demonstrate some of the important Characteristics, as a part of Driver needs for adjusting or modifying a behavior in order to meet new situations in emergency.

Also, the test method seems to fit in the tools presently used for Vehicle Dynamics analysis and calculations. The Axiomatic Design method is well accepted for its focus on functionality in the final Products and therefore it seems suitable to combine the suggested test method for improved functionality development with further Driver Modeling.

The importance of starting at a correct level when decomposing the Functional Requirements is demonstrated in this study. Maybe this is the key problem for Vehicle Engineers since it requires multidisciplinary competencies to be involved. The present work is performed showing that multidisciplinary competencies, such as Human Factors, Vehicle Engineering and M&S, can be assembled around a shared problem by using AD for structuring Driver Needs. Axiom # 2 in the AD method states that a robust solution has the least information and that is suggested to be the result of analyzing and quantifying the time needed for recovery. The least time needed for recovery could tentatively well correspond to Axiom # 2 with a minimum of information content used for decisions of what design parameter to be selected.

The values of 80-120 milliseconds used for a Vehicle response variation, found in validation of the test method, are assumed to be applicable only on young Drivers in combination with the Vehicle Model in use. The validation is of an explorative type demonstrating the method. In order to be reliable in use on Real life safety matters further studies are recommended, investigating differences in aged and novice Drivers too. It must be stated that not even the best existing Driving Simulators can replace real life testing disregarding the fact that real life testing is impossible due to risks of personal injury and property damage. Hopefully, this study is inspiring for future cross-disciplinary work for common Product developments where human beings are considered to be responsible for its usage.

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