Objectifying Ride Comfort in Autonomous Driving

An extended Model of the ISO-2631 Standard to Objectify the Ride Comfort of an Inattentive Occupant

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Abstract In order to objectify driving comfort in autonomous driving, an extended model of the existing ISO-2631 standard has been developed, analyzed and tested in the presented work. Therefore the conventional measuring points are extended by the head. For the objectification of the driving comfort a further differentiation for the k-factors is suggested in the weighting. Subsequently the calculated effective values are assigned to a 6-step scale. A first review of the presented method is carried out in a driving simulator experiment with 50 persons. The subjects drove through 5 sections with different vertical dynamic road excitations in an inattentive state and rated the driving comfort on a 7-step Likert scale. Simultaneously a body measurement technology is used to record the movements of the occupants using initial sensors. The evaluation of the results shows that the extended model reproduces the occupant comfort ratings evaluated as ordinal data more accurately than the existing ISO-2631 standard.

Keywords: Ride comfort, Whole Body Vibrations, Objectification, ISO-2631, Autonomous Driving.

1 Introduction

With the progressive advancement of autonomous driving systems, the occupant is becoming the focus of research and development. The different level of attention and the possibility for new activities of the occupant while driving, influence the requirements on the interior concept and vehicle configurations [7, 15]. An important part is the improvement of the ride comfort and the driving dynamics of the vehicle [9]. According to Bubb's comfort pyramid, comfort is referred to as the interaction of smell, light, vibration, noise, climate and aesthetics [1]. This is strongly influenced by the driving dynamics, with its subsections of longitudinal, lateral and vertical dynamics. These directions play a key role in the occupant movement's as well as the acoustics occurring in a vehicle [16]. It can be assumed that through the ongoing improvements in creating comprehensive and consistent environmental models as well as the computation of the trajectory of an autonomous vehicle, longitudinal and lateral excitation can be significantly reduced.

Especially in one of the first possible applications of autonomous vehicles: a long car journey on the highways with a constant speed and less lane changes. At the same time, vertical dynamics and vibration comfort, as well as their objectification in autonomous driving, become more important. For this reason, it is fundamental to concentrate on the vibration comfort during autonomous driving.

1.1 Motivation and Goals

Previous studies and investigations have shown that the head movements of an inattentive occupant, in this case distracted by a secondary activity, increase significantly compared to an attentive driver with the same road excitation [3, 6]. In addition, it could be shown that the best results can be achieved by objectifying ride comfort according to the ISO-2631 standard in comparison to other methods [6]. Combining both statements, it becomes necessary to consider the head as measurement point for objectifying ride comfort. In the past, the objectification of comfort by head movements has been rejected due to a lack of significance [13]. This could change on the basis of these results and in the scope of autonomous driving. The aim of this work is therefore to achieve improved values in the objectification of ride comfort in an autonomous driving scenario by extending the ISO standard by the measuring point head.

1.1 Structure of the Paper

This paper is divided into five sections. The first gives a introduction of the backgrounds and summarizes the motivation and goal of the paper. Section two analyses the current state of research in the objectification of ride comfort in passenger cars with respect to autonomous driving. Section three describes the methodology for the body measurement system, the modified model and the conducted study. In section four, the results are presented and analyzed, followed by a conclusion and outlook of the presented work in section five.

2 State of the Art

Comfort is a strongly subjective feeling, which varies essential between people and is characterized by personal inclinations. Herzberg [10] has defined comfort as the absence of discomfort with the result that only discomfort exists and comfort represents only the absence of discomfort. The reduction of discomfort, however, does not necessarily lead to a positive influence on comfort, which also includes aesthetic aspects and depends on well-being and relaxation [18]. There is no clear separation or scale for comfort perception. That makes it difficult to record the sensation of comfort. Many studies and surveys have been performed to measure comfort. Usually, the data are measured with ordinal or interval scales. Ordinal scales, also called rank scales, arrange the values in an order of standing. For this, a statement cannot be made about the absolute distances between the results (given answers). In the comfort rating, this means that the ratings have different distances within a scale. If, for example, a 7-step scale from 0 to 6 is used, the distance between an evaluation between 1 and 2 in a subject is different in a ratio (distance) than from the 4 to the 5 scale. A particularly common ordinal scale is therefore the Likert scale [8]. For interval scaled data, statements can be made about the absolute distances between the values, but without a meaningful zero point. An example of this is temperature [4]. The distance between 10 and 20 degrees is the same as the distance between 30 and 40 degrees. However, it should be noted that 40 degrees is not twice as warm as 20 degrees. Even though the Likert scale for evaluating comfort actually collects ordinal data, these are often treated incorrectly as interval-scaled data. In regard on whole-body vibrations, one of the most popular methods for objectifying comfort is the ISO-2631 standard. It describes methods for evaluating periodic, stochastic and transient whole-body vibrations in relation to health and comfort in a frequency range between 0.5 – 80 Hz. For the evaluation of the vibration comfort, only acceleration values at certain points and directions of introduction are required. Accelerations are measured at the seat rail, seat cushion, backrest and feet. In addition, the angular accelerations around the three axes are included in the evaluation at some measurement points. A frequency-dependent evaluation function is defined at each point of introduction and direction in order to map the human perception of the vibrations. Figure 1 illustrates the sequence of a comfort evaluation from the measurement as input to the classification and categorization as output.

The most important parameter for the evaluation of vibration comfort is the overall vibration total value. This parameter can be calculated from the quadratic mean value of the weighted vibration intensity of the individual measuring points (point vibration total value) [11]. As already the overall vibration total value, the point vibration total value, can be determined from the quadratic mean value of the individual directions multiplied by a weighting factor k. For the determination of the discomfort sensitivity for multiaxial excitations, the factor k weights the influence of the oscillation at the respective measuring points to varying degrees.

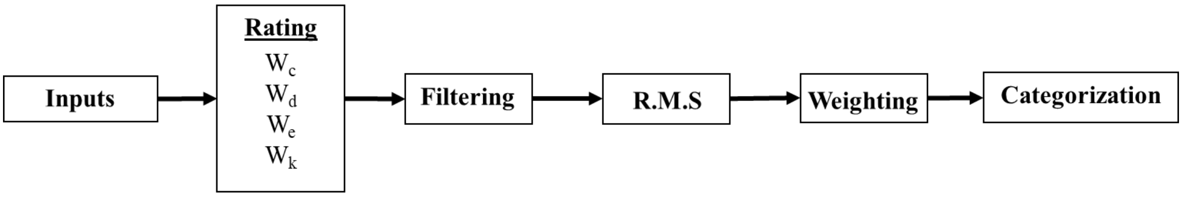

Fig. 1. Sequence of a comfort evaluation from the measurement to the categorization according to the ISO-2631 standard.

Though, as described above, the weighted root-mean-square (RMS) is the most commonly used basic method. The ISO contains a rating table for the discomfort rating. The overall vibration total value intensity changes according to the basic method can be compared with a scale to assign the assumed subjective evaluation of the occupants. Therefore the subjectively felt vibration comfort caused by the mechanical vibrations is set in connection with the vibration strength. The ISO scale indicates that there are overlaps between the individual areas [10]. This makes it more of an orientation than a strictly defined illustration of the subjective comfort value. The difficulty is caused by translating subjective sensations into objective measured values.

3 Method

The first part of this section describes the body measurement system. It illustrates, what is used to record and evaluate the movements of the inattentive occupants and the vehicle while driving and as well the basis of the ongoing research work. In a second part, an extension of the existing ISO-2631 standard is proposed, which includes further measuring points on the occupant's body. The aim is to increase the accuracy of the objectification of ride comfort in an autonomous journey. In the last part, a study is conducted in the driving simulator in order to collect body movement data on the occupant and his comfort impression.

3.1 The Body Measurement System

The body measurement system (BMS) allows the recording of occupant movements while driving in real traffic as well as driving in simulator. It can be used on an attentive driver as well as on an occupant who is distracted by e.g. a secondary task. A detailed description of the system can be found in Burkhard [2]. Comparable systems have been developed independently by DeShaw and Rahmatalla [5, 14]. As shown in Figure 2, a sensor is attached to the head of the subject with a safety cap. Further sensors are with a strap on the subject's chest and with a seat cushion on the seat pad. Another sensor is attached to the seat rail.

Fig. 2. Occupant in the driving simulator with sensors on head, chest, seat cushion and seat rail.

At the person’s head and on the vehicle body capacitive six degree of freedom sensors Dytran© 7556A1 are used. These combine a triaxial capacitive accelerometer with a gyroscope. The detected frequencies are in the range of 0 to 800 Hz for the accelerations and 0 and 150 Hz for the angular accelerations.

On the chest triaxial a capacitive acceleration sensor PCB Piezotronics® 3713E 1125G is used. However, this sensor will not be considered further in the following evaluation. To measure the seat pad as necessary for the ISO-2631 standard, a compliant seat cushion according to ISO-10326-1 [12] is used with a PCB Piezotronics® 356 A16 sensor. The sampling rate of the measurement unit is set to its maximum of 1000 Hz. Recorded data from the sensors can be evaluated in the initial local coordinate system. This does not allow conclusions about the actual relative acceleration to the vehicle. To make the data of head and vehicle comparable, it must be transformed into a standardized global coordinate system. For this purpose, a complete data set of all subjects is created. Subsequently the data set is automatically transformed into a uniform coordinate system, synchronized and cut according to individual measuring sections. The triaxial sensors cannot be transformed due to the missing rotation rate and are only cut and synchronized. The direction of view during driving is not determined.

3.2 Design of an Extended Model

In order to be able to assess driving comfort even when driving autonomously and thus with an inattentive occupant, an extended model of the ISO-2631 standard was developed. In addition to the conventional measurement data, this model includes an assessment of the head movement. The following Figure 3 shows the sequence of an evaluation from the measurement as input to the categorization. In order to prove the fundamental effectiveness of the model, the input variables in this paper were limited to the seat cushion and the head of an occupant. In the following, these were also limited for evaluation according to the existing ISO standard. A preliminary investigation has shown that the measurement of the vehicle body does not improve the evaluation according to both methods. This can be explained by the fact that the body movement of all subjects is identical due to the simulator used, but results in different ratings.

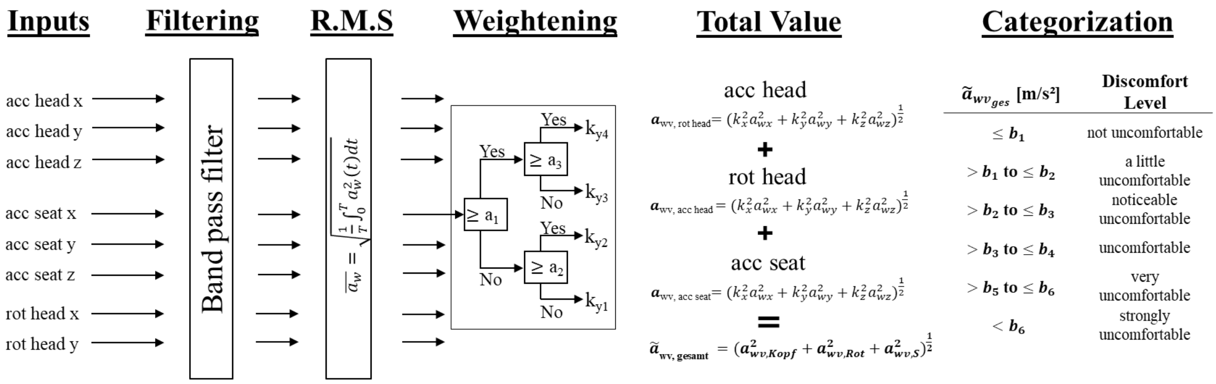

Fig. 3. Sequence of an extended comfort evaluation model that includes the head movements.

The input variables pass in accordance with the ISO-2631 standard through a first band pass filtering and are combined to a total value (RMS) depending on their direction of movement. The factors are classified and weighted depending on their intensity. The appropriate k-factors are selected accordingly. This means that higher movements can also be weighted more strongly. A total value is calculated and assigned to an extended, 6-step scale. For this first experiment, the a-, k- and b-values were determined empirically. In the future, the values can be calculated by mathematical methods for a higher number of subjects. In the outlook section, this is briefly discussed. The different empirical values used for this experiment are described in Table 1 below.

Table 1. RMS values averaged over all 50 subjects at seat rail and head.

a-value			k-factor				b-value				
a_1	a_2	a_3	k_1	k_2	k_3	k_4	b_1	b_2	b_3	b_4	b_5
	in m/s²								*in m/s²*		
1	0.75	2	0.75	1	1	1.25	1.25	2.25	3	3.75	4.25

3.3 Objectification in a Driving Simulator Study

In order to generate real data for the development of an extended model of the ISO standard and to be able to evaluate it, the study is conducted in a driving simulator. Real road measurements with a BMW 750 Li (G12) were performed on five straight sections at 70 km/h. The vehicle movements were recorded with a high-precision gyro platform (GeneSys Elektronik ADMA-G-PRO+). Section 1 has damaged pavement layers with many provisional repairs that lead to strong heave, pitch and roll motion. Section 2 is an undulating road that results in low-frequency heave and pitch motion of the vehicle body. Section 3 has damaged surface layers at the roadside that result in roll motion with subsequent head toss movements. Section 4 is a recently asphalted road with minimal excitation. The last section 5 is quite similar to section one. The data is transferred to a dynamic driving simulator of the BMW Group. This consists of a half vehicle mockup on a hexapod, which is coincidently moved by a tripod in the plane. It can oscillate on a frequency range from 0 to 30 Hz in all directions. The mockup moves in front of a static screen in which the corresponding driving environment is visually shown. The visual environment was modeled according the real roads. Acoustically, the rides over each section was recorded and played back in the driving simulator. The optics, acoustics and excitations were subsequently synchronized and offline motion cued in the simulator. All sections can be permuted in their sequence accordingly. The synchronicity and authenticity were confirmed accordingly by experts from the driving testing.

In the context of the study as within-subject-design, 79 subjects participated over a period of three weeks. An error analysis resulted in a total of 50 valid data sets. Every subject experienced each excitation for 30 sec and subsequently rated their comfort sensation. In order to create a distraction for the participants, they were instructed to complete a survey about personal details on a 12.3 inches tablet. The task and the measurements were monitored by the investigator sitting in the control room. In order to collect objective data, measurements were performed on the inattentive occupants using the body measurement system. To determine the subjectively experienced discomfort of an excitation, a 7-step unipolar Likert scale with verbal marks from zero to six was used. Anchorpoints for the grading scale were “0 - no disturbance” to “6 - very strong disturbance”. All subjects were employees of the BMW Group with no deeper experience in autonomous driving or ride comfort. Table 2 shows statistical data of the sample composition. To be complete, further hypothesis and variants were investigated in the study. Due to the study design, the parts can be viewed separately.

Table 2. Sample composition of the study – 50 subjects, 20% female.

	Age *in years*	**Height** *in cm*
Mean	35	180
Std	12.90	9.51
Min	19	153
Max	60	198

4 Results and Discussion

A comparison of the measurements on the seat rail, seat cushion and head in Table 3 shows the differences in the accelerations of an inattentive occupant. The RMS accelerations and rotation rates on the head are significantly higher on all sections than on the seat rail in a paired comparison. The average acceleration at the head is 0.57 m/s^2 higher than the acceleration at the seat rail. On the other hand, the accelerations on the seat rail and seat cushions are in the same range. A clearer picture emerges when looking at the rotation rates. The average acceleration at the head is 13.42 °/s above that at the seat rail in a paired comparison. Unfortunately, it is not possible to make a statement regarding the seat cushion and seat rail. The limited size of the sensor does not allow the integration of a gyroscope. It can be estimated that only minor differences would exist. It can be assumed that the high head movement results from the limited perception of the drive. Thus, the occupants do not have the capability to perceive and assess any excitation in advance. They can only react to the excitations in a compensatory way and must also rely on their sense of balance. Zikovitz and Harris came to a similar result in their research about the perception of longitudinal and lateral dynamics [17].

Table 3. RMS values averaged over all 50 subjects at seat rail and head.

RMS	Seat rail						Seat cushion			Head					
	a_x	a_y	a_z	ω_x	ω_y	ω_z	a_x	a_y	a_z	a_x	a_y	a_z	ω_x	ω_y	ω_z
	in m/s²			*in °/s*			*in m/s²*			*in m/s²*			*in °/s*		
Section 1	0.21	0.71	0.68	2.61	2.50	0.30	0.30	0.61	0.69	1.18	1.46	1.05	22.54	15.71	17.94
Section 2	0.19	0.38	0.58	1.60	2.83	0.20	0.27	0.34	0.58	1.13	0.96	0.89	15.44	13.25	15.53
Section 3	0.18	0.50	0.62	2.20	2.40	0.20	0.26	0.45	0.61	1.07	1.25	0.93	20.58	15.38	15.74
Section 4	0.07	0.23	0.23	1.10	0.80	0.10	0.10	0.21	0.23	0.51	0.61	0.44	9.11	8.96	7.50
Section 5	0.13	0.52	0.42	2.10	1.30	0.20	0.19	0.45	0.43	0.84	1.17	0.69	18.69	12.99	12.41

An evaluation of the subjective data allows a comparison with the newly developed extended model and with the current ISO-2631 standard. The subject's ratings shown in Figure 4 and the objective values were processed as ordinal data in box plots. The rating of the sections corresponds thereby to the expectations of the selected excitations (cf. Chapter 3.3). The damaged pavement layers on section 1 are rated the worst, the recently asphalted road of section 4 are rated best. It is interesting that the recently asphalted section 4 is still rated as disturbing.

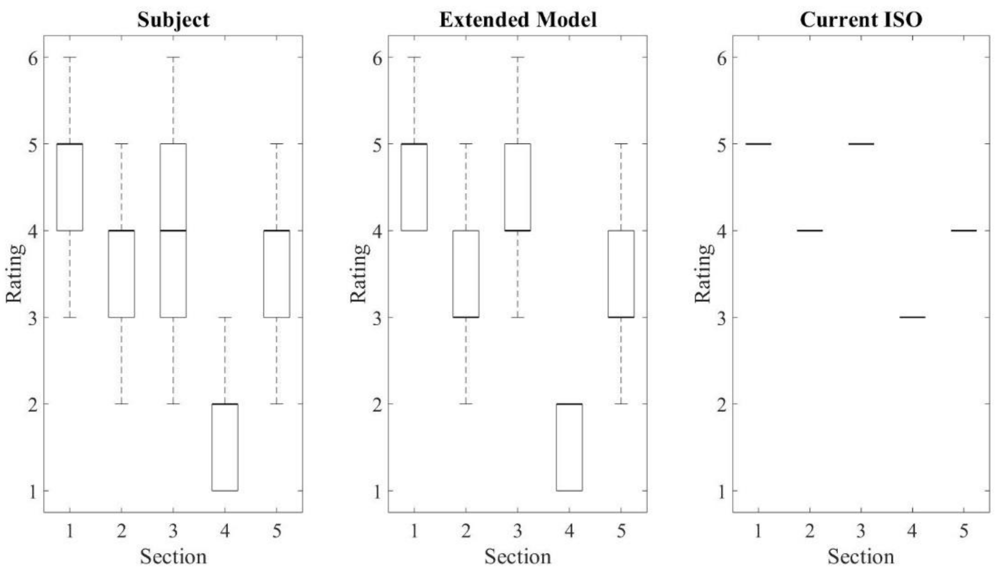

Fig. 4. Boxplot of the evaluation of the subjects, the calculation with the extended model and the current ISO.

If the objectification is compared according to an extended model with the current ISO, the extension allows, in addition to the actual comfort value as median, also to calculate the upper and lower maximum values as well as quartiles. In addition, it is noticeable that the evaluation of the extended model is slightly better than that of the current ISO. A representation of the corresponding numerical value is summarized in the appendix in Table A. In order to compare the objectification methods, a sign test is made between the subject's rating and the objectification methods. For this purpose, an observation is performed across all sections. The results in the form of significance and z-score are described in Table 4.

Table 4. Comparison of the objectification procedures to the real ratings with a sign test.

	Section 1		Section 2		Section 3		Section 4		Section 5	
	ExtMdl vs Subject	*CurISO vs Subject*	*ExtMdl vs Subject*	*CurISO vs Subject*	*ExtMdl vs Subject*	*CurMdl vs Subject*	*ExtMdl vs Subject*	*CurISO vs Subject*	*ExtMdl vs Subject*	*CurISO vs Subject*
Significance	0.42	0.03	0.28	0.09	0.11	0.00	0.82	0.00	0.49	0.08
z-score		-2.16	-1.08	-1.70		-3.95		-6.33	-0.70	-1.74

The results underline that by the current ISO three out of five indicate a significant difference between the subjective impression and objective measurement (Table 4, grey). In comparison the new method has no significant effect. It can be assumed, that the extended model display the subjective data better. As well the extended model gives the trend, that there is no difference between objective and subjective measurements.

5 Conclusion and Outlook

The results of the experiment show that the inclusion of the occupant's head as measurement point can lead to an improvement in the objectification of driving comfort. Even if this was not considered in the past due to only a small influence on the objectification result, it becomes more pertinent in an autonomous vehicle. The reduced degree of attention of the occupants about the route of the drive leads to significantly higher accelerations at the head of the occupants. This makes the head a respectable measured quantity. The evaluations show that the inclusion of the head creates better results in a distracted state than the conventionally used ISO-2631 standard. It must be taken critically into account that the experimental group is a supposedly small sample of 50 persons on five sections. Furthermore, the evaluation of driving comfort, also in the driving simulator, is very subjective, not all external variables can be recorded and also the comfort cannot be measured directly. Therefore, external and environmental factors, as well as the biometrics of the subjects, expectations and experience can influence the results. Last but not least, the seat rail cannot be included as a measured variable due to the always identical body movement of the driving simulator. This leads to a possible influence on the evaluation. In order to account for these shortcomings, data sets from further experiments will be used. This allows the number of subjects to be increased to over 200 on different sections and excitations. Likewise, data from field experiments will be used in the future to allow a measured variable to be studied on the seat rail. In order to improve the accuracy of the extended model, the empirically determined variables a, k and b will be replaced by mathematical calculations. This is possible through increasing the number of test persons. Methods such as k-means clustering are used to calculate the a- and b-values. To determine the k factors, optimizers such as the brute force approach are applied. This should make it possible to objectify the driving comfort of occupants in an autonomous vehicle.

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Contributions First author Georg Burkhard was initiator of the study and involved in the idea and development of the extension of the ISO standard with a body based objectification approach. Second author Tobias Berger created the expansion of the ISO together with the first author conducted the evaluation within the scope of his thesis work. Third author Erik Enders was involved in the planning and analysis of the study as well as the development of the body measurement system. Dieter Schramm made essential contributions to the conception of the research project and revised the paper critically for important intellectual content. Dieter Schramm gave final approval of the version to be published and agree to all aspects of the work. As guarantor, he takes responsibility for the overall integrity of the paper.

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Appendices

Table A. Comparison of medians and frequencies.

		Section 1			**Section 2**			**Section 3**			**Section 4**			**Section 5**		
		Sub	*Ext*	*Cur*	*Sub*	*Ext*	*Cur*	*Sub*	*Ext*	*Cur*	*Sub*	*Ext*	*Cur*	*Sub*	*Ext*	*Cur*
	Median	5	5	5	4	3	4	4	4	5	2	2	3	4	3	4
	Sum	43	43	43	50	50	50	41	41	41	46	46	46	47	47	47
Frequency Rating	**0**															
	1										20	19		8		
	2				6	2		3			22	27		14	3	
	3	6			13	27		9	6		4		46	14	22	47
	4	13	17		22	16	50	15	16					11	21	
	5	17	17	43	9	5		10	18	41				7	1	
	6	7	9					4	1							