Investigating the Subjective-Objective Correlation about On-center Handling Characteristics Using Response Surface Method

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***Abstract*—A better understanding of the correlation between subjective and objective measures of vehicle handling is critical for vehicle dynamics research. This paper presents a methodology seeking to correlate the subjective and objective measures of vehicle handling, especially of on-center handling quality. Firstly, eighteen objective matrices which correlate with the on-center handling performance were measured for twelve different experimental vehicles. Secondly, these twelve experimental vehicles were evaluated by a professional driver to obtain the subjective performance ratings about on-center handling characteristics. Lastly, a response surface model was developed to represent the relationship between the subjective performance (ratings) and the objective measures, for each subjective performance measure/matrix. Radial Basis Functions (RBFs) are adopted in this regard. Cross-validation technique was used during the process of the response surface models development, to evaluate the accuracy of the developed response surface models. The resulting models could be uniquely helpful for engineers to streamline the design and development process.**

Keywords-subjective and objective correlation; response surface; on-center handling; vehicle dynamics; radial basis functions

I. INTRODUCTION

Handling characteristics have great impact on the closed-loop system of vehicle driving. Primary characteristics for handling performance analysis include: (i) steering wheel angle, (ii) steering wheel torque, (iii) yaw velocity, (iv) roll velocity or roll angle, and (v) lateral acceleration.

Vehicle handling performance, the dynamic response of an automobile to driver inputs, can be described in terms of: (i) subjective feedback from drivers (or subjective handling), (ii) measured objective data, and (iii) mathematical relationships between objective and subjective characteristics. Subjective handling refers to driver opinions of how the vehicle responds to his or her hand wheel, throttle and brake inputs while performing driving tasks.

On-center handling refers to the steering behavior on and about the straight ahead driving position, and is particularly important at higher speeds where it has become a major safety and refinement issue. Most of the driving lies in the straight ahead position with a small lateral acceleration (below 0.2g). The steering feel in this range, named "on-center feel", is of particular interest in evaluating the controllability and driving comfort for highway driving.

A. Literature Review

Norman [1] presented a technique of measuring parameters that correlate the "steering feel" and the vehicle response. No reference is made to the steering wheel activity or subjective evaluations; an objective performance test program was carried out but the analysis was performed in respect to the type of vehicle and country of origin.

Deppermann[2] addressed the measurement of some of the parameters describing the steering wheel activity, and proposed a method for quantifying "steering feel". Analysis was performed to evaluate the relationship between the objective and subjective responses.

The Motor Industry Research Association (MIRA) [3] conducted a collaborative research program to establish an objective measurement technique for on-center handling quality. By considering the process by which on-center handling is evaluated subjectively, a number of elemental characteristics have been identified.

A previous linked research project between the University of Leeds and the MIRA contributed to the subjective-objective correlation debate, and has resulted in the collection of substantial test data available for the project [4].

Bergman [7] was the first to use open loop tests for subjective data collection and closed-loop test to capture vehicle objective metrics for handling performance evaluations.

B. Motivation and Objectives

For improvements to be made in the development cycle of any road vehicle, the understanding of subjective and objective vehicle behavior must be further understood. Improved links between subjective and objective measures of vehicle behavior would substantially aid vehicle development engineers by

978-1-4673-275-0/12/$31.00 ©2012 IEEE

being able to predict subjective assessments using vehicle simulations.

An underlying goal of this work is to demonstrate how a relatively simple mathematical model, suitable for effective use at the early stages of vehicle design, could be used to predict both the objective responses and the subjective feel of the car. The first goal of the work is to correlate subjective opinions of professional drivers with objectively measurable vehicle responses, especially for on-center handling quality. A response surface method is implemented for this purpose.

The second goal is to validate a vehicle handling model suitable for use by engineers during the design and development phases of vehicle production.

The remainder of the paper is organized as follows. Section II presents the experimental/objective data of on-center handling. The details of the subjective characteristics are discussed in Section III. Section IV develops the response surface models investigating the correlation between subjective and objective handling performance. The results and discussions are given in Section V.

II. EXPERIMENTAL/OBJECTIVE DATA COLLECTION

This section describes experimental vehicles used to collect objective performance data, as well as tests performed to characterize the on-center handling. It is important to test the vehicle models and to correlate subjective ratings over a wide range of operating conditions, for the sake of capturing broadly-based conclusions. Thus, setups of the twelve experimental vehicles are specified to extend the range of the handling response, for both the model validation and the subjective-objective correlation work.

Eighteen matrices are selected to represent the objective performance of handling, which is showed in Table 1. Twelve differing cars are used for the experiment. Table 2 shows the values of the objective performance matrices for each car.

III. SUBJECTIVE DATA COLLECTION

Matsushita [5] argues that although trained drivers are highly skilled drivers as well as good assessors, their vehicle handling preferences might be different compared to normal drivers. Weir & DiMarco [6] designed an experiment to compare the subjective feedbacks from an expert driver and sixteen ordinary drivers. The results showed that the expert driver preferred a more responsive vehicle compared to the ordinary drivers.

During the subjective test sessions, the main target is to build a database of subjective ratings. The collection of data is guided by a questionnaire. By this means, all judges express their feelings in a comparable way. A framework is developed to obtain the subjective ratings of a car, by observing the following sequence of three steps.

(1) The driver is given the questionnaire before testing to understand what feedback is required, so that he/she could conduct suitable maneuvers during the evaluation.
(2) The professional driver drives the experimental car on the proving ground, and can freely determine what circuits and maneuvers to perform without any particular time constraints.
(3) The questionnaire is completed by the driver in the last step. Ratings are given according to the referenced car.

The time line in Fig. 1 shows the main contributors to the rating scale development over the last forty years. There follows a brief description about the scales, highlighting problems, and the ways in which they have been improved.

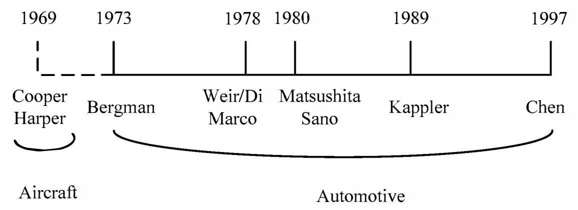

Figure 1. Key contributors to the rating scale development

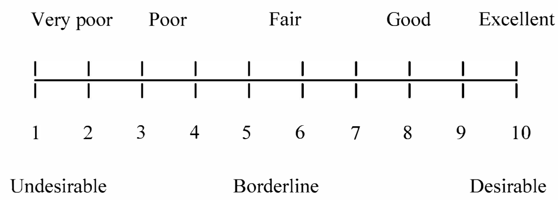

Figure 2. *SAE ratings scale*

Figure 2 shows the rating scales recommended by the Society of Automotive Engineers (SAE). It is a ten point, continuous, bipolar scale which neither defines a question nor the dimension to be related. The scale only has one verbal terminal anchor, "excellent". Another criticism is that "very poor" is not counterbalanced by having "very good". Both points mentioned result in a scale that has non-symmetry. Handing qualities of vehicles on the market today hardly cover "borderline" rated vehicles so only the "good" half of the scale is used. Since the extreme end of the scale is rarely used, the usable or effective scale length is reduced to four points (6-9).

In the current paper, eleven subjective standards are chosen to evaluate the handling performance of vehicle. We use the usable or effective scale "6-9 score" to judge the car's performance. The subjective rating results for twelve experimental cars are shown in Table 3.

TABLE I. OBJECTIVE TEST METRICS

Test	group	Derived Metrics	Description
On-center Test	steering wheel angle/lateral acceleration (SWA/LA)	DAm [deg/g]	Average slope at coordinate origin
		DAarea [deg·g]	Area of graph
	steering wheel torque/lateral acceleration (SWT/LA)	CAmi [Nm/g]	Average slope at coordinate origin
		CAcv0 [Nm]	Steering wheel torque at zero lateral acceleration
		CAmf [Nm/g]	Upper slope of sluggish curve at maximum lateral acceleration (0.15g)
		CAmr [Nm/g]	Lower slope of sluggish curve at maximum lateral acceleration (0.15g)
		CAcvf [Nm]	Upper value of sluggish curve at maximum lateral acceleration (0.15g)
		CAcvr [Nm]	Lower value of sluggish curve at maximum lateral acceleration (0.15g)
		CAarea [Nm·g]	Area of graph
	yaw velocity/steering wheel angle (YV/SWA)	PDm [1/s]	Average slope at coordinate origin
		PDarea [deg²/s]	Area of graph
	steering wheel torque/steering wheel angle (SWT/SWA)	CDmi [Nm/deg]	Average slope at coordinate origin
		CDcv0 [Nm]	Steering wheel torque at zero steering wheel angle
		CDmf [Nm/deg]	Upper slope of sluggish curve at maximum steering wheel angle
		CDmr [Nm/deg]	Lower slope of sluggish curve at maximum steering wheel angle
		CDcvf [Nm]	Upper value of sluggish curve at maximum steering wheel angle
		CDcvr [Nm]	Lower value of sluggish curve at maximum steering wheel angle
		CDarea [Nm·deg]	Area of graph

TABLE II. OBJECTIVE PERFORMANCE DATA OF 12 EXPERIMENTAL VEHICLES

Objective Matrices	Values											
	1	2	3	4	5	6	7	8	9	10	11	12
Dam [°/g]	41.10	59.30	71.60	83.80	78.77	58.63	54.37	66.64	77.72	96.50	78.60	69.64
Daarea [°·g]	1.80	1.79	0.92	1.64	0.64	1.79	1.64	1.63	2.58	1.39	0.87	2.28
CAmi [Nm/g]	8.36	8.18	19.73	14.07	20.92	14.26	11.45	14.99	15.32	10.77	15.95	12.61
CAcv0 [Nm]	3.89	3.67	3.47	3.40	1.91	2.78	3.17	4.34	3.31	2.90	2.76	3.52
CAmf [Nm/g]	3.96	0.99	-4.41	-0.04	4.43	-2.23	-0.63	-4.24	-0.67	6.84	1.71	-0.17
Camr [Nm/g]	28.20	22.94	16.63	22.38	11.22	17.66	20.25	23.24	28.77	19.21	10.65	31.00
CAcvf [Nm]	2.67	2.41	3.15	2.79	3.13	2.41	2.40	3.06	2.74	2.71	2.91	2.59
CAcvr [Nm]	0.66	0.45	1.32	1.12	1.75	1.18	0.86	0.85	1.72	0.77	0.84	1.49
Caarea [Nm·g]	0.98	0.93	0.88	0.85	0.52	0.68	0.79	1.09	0.76	0.77	0.76	0.81
PDm [1/s]	0.36	0.27	0.26	0.20	0.24	0.29	0.29	0.32	0.31	0.19	0.25	0.25
PDarea [deg²/s]	25.58	20.60	13.74	4.88	8.33	26.06	28.18	27.20	12.84	19.38	20.11	31.52
CDmi [Nm/°]	0.24	0.19	0.29	0.22	0.27	0.23	0.21	0.25	0.23	0.16	0.21	0.24
CDcv0 [Nm]	1.66	1.96	2.07	1.72	1.08	0.77	1.41	2.21	0.58	1.84	1.97	0.81
CDmf [Nm/°]	-0.05	-0.07	-0.09	-0.04	0.05	0.00	-0.06	-0.10	-0.04	0.02	0.07	-0.07
CDmr [Nm/°]	0.13	0.07	0.03	0.09	0.09	0.02	0.00	-0.07	-0.10	0.09	0.25	-0.04
CDcvf [Nm]	2.72	2.33	3.27	2.68	3.40	2.60	2.43	3.04	2.46	2.49	3.17	2.43
CDcvr [Nm]	2.45	1.42	2.14	1.86	2.66	1.99	1.45	1.10	1.42	1.16	2.57	1.84
Cdarea [Nm·°]	35.93	48.16	52.63	42.65	29.13	21.43	37.96	63.53	21.93	50.21	45.48	21.96

TABLE III. SUBJECTIVE PERFORMANCE DATA OF 12 EXPERIMENTAL VEHICLES

Questions about subjective response	Ratings											
	1	2	3	4	5	6	7	8	9	10	11	12
Returnability	7.0	6.8	7.2	6.7	8.1	6.5	6.5	6.0	7.0	7.3	6.5	6.3
Deadband	7.5	6.8	7.0	7.0	8.1	6.5	6.8	6.8	6.3	7.0	7.0	6.3
Steering friction feeling	7.7	6.8	6.8	6.7	8.1	6.8	6.5	6.0	7.0	6.3	6.3	6.8
On-center effort feeling	7.7	6.2	7.2	7.0	7.7	7.0	6.7	6.5	6.8	6.0	6.5	6.3
Effort build-up	7.8	6.2	7.2	6.7	7.7	6.8	6.5	7.0	7.0	6.8	6.0	6.8
Effort level	7.3	6.8	6.8	6.5	7.7	6.7	6.7	6.5	7.0	6.5	6.5	7.0
Effort linearity	7.0	6.2	7.3	6.8	7.7	6.5	6.3	6.5	6.8	7.0	6.3	6.5
On-center response	7.5	6.8	7.0	7.0	8.0	7.0	6.5	6.8	6.5	6.5	7.0	6.3
Response linearity	7.3	6.8	7.2	6.8	7.6	6.3	6.3	6.5	6.8	6.5	6.8	7.3
Kick back	7.8	6.0	6.3	6.8	7.6	6.7	6.8	7.0	7.3	7.3	6.8	7.0
Steering angle	7.2	6.0	6.7	6.7	7.6	6.7	6.7	6.8	6.8	6.3	7.0	6.5

IV. CORRELATION BETWEEN SUBJECTIVE AND OBJECTIVE RESPONSES

The objective and subjective information about on-center handling performance has been collected in the previous sections. A response surface model is developed to investigate the subjective-objective correlation in this section. The response surface model represents the relationship between the subjective performance (rating) and the objective measures, for each subjective performance evaluation measure. The Radial Basis Functions (RBFs), which has been shown to be a robust response surface technique, is adopted in this paper. Cross-validation technique is used during the development process of the response surface models, to evaluate the accuracy of the models.

A. Radial Basis Functions

The idea of RBFs as approximation functions was introduced by Hardy [8] in 1971, where he used the multiquadric RBFs to fit irregular topographical data. Since then, RBF has been used for various applications that require global approximations of multidimensional scattered data [9-12].

RBF is expressed in terms of the Euclidean distance, $r = \left\| x - x^i \right\|$, of a point x from a given data point, x^i. One of the most effective forms is the multiquadric function [8,11,12], which is defined as

$$\psi(r) = \sqrt{r^2 + c^2} \quad (1)$$

where $c > 0$ is a prescribed real valued parameter. The final approximation function is a linear combination of these basis functions across all data points, as given by

$$\tilde{f}(x) = \sum_{i=1}^{n_p} \sigma_i \psi\left(\left\| x - x^i \right\| \right) \quad (2)$$

where σ_i's are unknown coefficients (to be determined), and n_p denotes the number of selected data points. In this case, the number of coefficients is equal to the number of sample points, n_p. Equation (2) can be solved using pseudo inverse method.

B. Cross-Validation

A cross-validation error is the error at a data point when the surrogate is fitted to a subset of the data points not including that point. When the surrogate is fitted to all the other $p-1$ points, (so-called leave-one-out strategy), we obtain the vector of cross-validation errors, $\tilde{e}$. This vector is also known as the PRESS vector (PRESS stands for prediction sum of squares).

The leave-one-out strategy is computationally expensive for large number of points. We then use a variation of the q-fold strategy to overcome this problem. Q-fold strategy involves splitting the data (randomly) into q roughly equal subsets, then removing each of these subsets in turn and fitting the model to the remaining, aggregated, $q-1$ subsets. A loss function L can then be computed, which measures the error between the predictor and the points in the subset we set aside at each iteration; the contributions to L are then summed over the q iterations.

More formally, if a mapping $\zeta : 1, \cdots, n \rightarrow 1, \cdots q$ describes the allocation of the n training points to one of the q subsets and $\hat{f}^{-\zeta(i)}(x)$ of the predictor obtained by removing the subset $\zeta(i)$ (i.e. the subset to which observation i belongs), the cross-validation measure is (by introducing the squared error in the role of the loss function)

$$PRESS_{SE} = \frac{1}{n} \sum_{i=1}^{n} \left[y^{(i)} - \hat{f}^{-\zeta(i)}(x^{(i)}) \right]^2 \quad (3)$$

In practical terms, using fewer subsets has the added bonus of reducing the computational cost of the cross-validation process by reducing the number of models that have to be fitted.

TABLE IV. COEFFICIENTS OF RBFS FOR SUBJECTIVE-OBJECTIVE CORRELATION

Output (Subjective rating)	Coefficients for each training point											
	1	2	3	4	5	6	7	8	9	10	11	12
Returnability	-0.415	0.903	-0.933	-0.460	0.367	0.665	-1.456	1.973	-0.025	-0.221	1.418	1.421
Deadband	-0.696	2.396	0.708	-2.035	0.057	1.124	-2.868	0.702	1.149	0.601	0.953	1.016
Steering friction feeling	-0.795	0.620	0.033	-1.362	0.005	0.278	-0.755	1.501	0.641	0.923	1.386	0.708
On-center effort feeling	-1.324	3.120	0.263	-2.525	0.514	0.212	-2.875	0.927	0.559	0.927	1.210	1.871
Effort build-up	-1.504	3.173	0.001	-1.586	0.388	0.032	-1.740	0.654	0.909	-0.335	2.056	1.121
Effort level	-0.201	0.998	0.174	-0.948	0.318	0.845	-1.494	1.113	0.589	0.850	0.704	0.230
Effort linearity	-0.729	2.347	-0.513	-1.325	0.569	0.352	-1.629	1.190	0.669	-0.301	1.524	0.932
On-center response	-0.473	0.972	0.752	-2.034	0.303	-0.746	-0.385	0.461	1.110	1.089	0.896	1.203
Response linearity	-0.010	0.350	-0.222	-1.100	0.604	1.174	-0.376	1.398	1.046	1.045	0.276	-0.995
Kick back	-1.529	5.181	1.592	-2.179	0.565	1.725	-4.150	0.061	0.342	-0.213	0.624	1.056
Steering angle	-0.681	3.726	1.171	-2.207	0.571	1.310	-3.795	0.266	0.415	0.967	0.049	1.114

V. RESULTS AND DISCUSSIONS

In this paper, the value of the prescribed parameter, c, is defined to be equal to 0.9 for all the eleven response surface models.

Table 4 shows the correlation results of subjective and objective responses, which gives the coefficients of the eleven RBF models. With the developed model, the engineers could better understand the customer's responses and requirements during the design and development process, thereby improving both the objective and subjective performance of the vehicle.

VI. CONCLUSION

This paper presents a methodology seeking to correlate the subjective and objective measures of vehicle handling, especially of on-center handling quality. A response surface model is developed to represent the subjective-objective correlation. The correlation results show that the subjective ratings have good relations with objective responses of vehicle, and we can improve the design method according to this correlation results.

In the future, more experimental cars should be tested to increase the size of the sample, which is a critical factor for response surface development. Future research should also investigate other types of response surface methods.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support by the National High-Tech R&D Program, China (No. 2007AA04Z131).

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