

Statistical Method for Identifying Factors Governing Vehicle Handling and Stability

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ABSTRACT

This research applied factor analysis to 13 quantitative evaluation indices used to evaluate vehicle handling and stability in an attempt to identify the structure existing among those indices. According to the results, the cumulative explained variance shows that 76% of the variance in the handling and stability indices is explained by a five-factor model comprising three factors related to vehicle driving characteristics and two factors related to steering feel. Using this five-factor model makes it possible to evaluate a comprehensive score for handling and stability from the measured evaluation indices and factor loadings. Furthermore, since this model allows for flexible adjustment of the weight of each factor based on the vehicle concept and evaluation objectives, it enables a quantitative evaluation of handling and stability tailored to the characteristics to be prioritized. This method systematically identifies the relationships among evaluation indices and has the potential to serve as a foundation for understanding the evaluation of handling and stability.

1. Introduction

Honda Motor has regarded technology as a means to contribute to human well-being, based on the philosophy of its founder, Soichiro Honda. In areas directly related to the quality of the driving experience, i.e. handling and stability, ride comfort, and noise and vibration, development efforts prioritize the driver's perception and the joy of driving. This commitment to customer value and essential qualities forms the foundation of Honda's research and development⁽¹⁾.

To investigate the joy perceived by customers and translate it into products, efforts have been made to introduce new survey methods⁽²⁾⁻⁽⁴⁾ and analytical techniques⁽⁵⁾ that objectively capture drivers' subjective evaluations, as well as to translate drivers' perceptions of handling and stability into objective indices.

With this background, Honda has been conducting research since the early 2000s in order to quantify subjective evaluations of handling and stability and ride comfort using physical indices. Because subjective evaluations of handling and stability cover a wide range of attributes, 13 indices are used to provide comprehensive coverage. Their application has advanced the development process by enabling handling and stability to be designed based on quantitative evidence from the planning stage of vehicle development.

Optimizing these numerous evaluation indices and setting design targets appropriately during the early

stages of development, however, requires a high level of specialized expertise. Furthermore, as the observed correlations among the indices suggest the existence of common latent factors, there has been a need to clarify the relationships among the evaluation indices and to provide a systematic understanding of the underlying structure of the handling and stability evaluation.

This research therefore applied statistical analysis methods to the accumulated data on the 13 indices used to evaluate handling and stability to clarify the essential value structure existing among the evaluation indices. Also, a factor model was proposed to identify the fundamental factors constituting an evaluation of handling and stability, and its validity was examined.

2. Method

2.1. Indices for Subjective Evaluations

The subjective evaluation indices analyzed in this research are listed in Table 1 and are used in vehicle development as handling-and-stability evaluation indices.

The evaluation set includes 13 indices, consisting of seven in Series A, five in Series B, and one in Series C, each under differing test conditions. These subjective descriptions relate to steering feel, such as steering feedback quality and initial steering effort during turn-in, as well as vehicle dynamic response, including the appropriate vehicle

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Table 1 Subjective evaluation indices for handling performance (13 indices, 140 samples)

ID	Index A1	Index A2	Index A3	Index A4	Index A5	Index A6	Index A7	Index B1	Index B2	Index B3	Index B4	Index B5	Index C
Subjective Evaluation Term	Steering Feedback Quality	Steering Torque at High Speed Turn	Appropriate Vehicle Response to Steer	Response Linearity to Steering Input	Responsiveness to Steering Input	Rear-Axle Response Fidelity to Steer	Perceived Cohesion of Vehicle Behavior	Steering Torque at Cornering Turn-In	Optimal Steering Effort at Turn-In	Appropriateness of Yaw Response	Linearity in Steering Response	Front-Axle Response Fidelity to Steer	Appropriateness of Understeer
Sample No.													
1	-0.75	0.47	0.51	-0.10	0.73	0.44	-1.11	-0.23	1.23	-0.23	0.46	-0.76	-0.84
2	-0.31	-0.13	1.63	-0.87	2.40	-0.09	-0.80	0.98	0.10	1.14	0.05	-0.72	-1.38
3	-0.19	0.10	0.33	2.23	1.22	0.95	2.33	0.25	0.26	-0.10	-0.99	1.15	0.07
4	-1.86	0.23	0.63	0.10	0.85	-0.03	-0.05	-0.83	-0.19	0.39	-0.27	-0.62	-0.93
5	-1.35	4.48	-0.34	-1.30	0.23	-1.35	-0.41	-0.30	-0.17	-0.30	0.70	-0.74	-0.31
6	-2.00	0.36	1.43	1.24	0.33	2.07	-0.68	-1.57	-2.97	1.40	-1.07	3.88	-0.03
7	-0.48	-0.06	1.60	0.13	2.73	0.99	-1.13	1.68	1.21	0.47	0.21	-0.76	-0.75
8	-0.67	0.86	-1.22	-0.93	-0.86	-0.66	-0.52	0.64	-0.18	-0.94	0.38	-0.33	0.46
136		-1.01						0.63	-0.23	-0.86	0.85	0.33	1.09
137	-4.45		3.89	2.86	-0.41	2.16	-0.23	-0.81	-0.08	2.80	0.86	1.75	-1.60
138	0.26	-0.17	0.75	-0.17	0.31	-0.15	0.45	-0.18	0.54	0.18	0.81	-0.22	-1.19
139	0.34	0.42	0.98	-0.24	0.43	-0.36	-0.34	1.30	0.23	0.45	-0.34	-0.02	-0.61
140	0.68	-0.64	2.40	-0.16	-0.78	-1.14	1.13	0.51	1.76	2.47	1.11	-0.93	-1.47
Ave	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
StdDev	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

response to steering and perceived cohesion of vehicle behavior and driver steering input.

Although each index is based on a measured physical quantity, standardized values derived from the mean and variance were used to facilitate comparisons of the degree of contribution in correlation and factor analyses.

2.2. Normality of Data

Since factor analysis is based on correlations among evaluation indices, it cannot accurately reproduce phenomena if the distribution of each index is extremely skewed.

Prior to this analysis, therefore, the normality of the distribution of each evaluation index, as well as the presence of any polarized data or extreme outliers, was examined.

The data distributions for the 13 evaluation indices are shown in Fig. 1.

All indices generally exhibited normal distributions, and no extreme outliers were observed. It was therefore concluded that, even without any special processing, no bias attributable to distribution characteristics would arise in the subsequent correlation and factor analyses.

2.3. Correlation Analysis among Indices

Since latent factor extraction in factor analysis relies on the correlations among indices, the correlations among the 13 indices were examined in Fig. 2.

When a correlation between indices exists, plotted data points are distributed in a linear pattern. Such correlations were confirmed to exist among multiple pairs of indices.

Table 2 shows the covariance matrix that quantifies these correlations. For standardized data, the covariance is equal to the correlation between indices. The data is displayed using a color gradient, with positive correlations shown in blue and negative correlations in red.

Focusing on Indices A3 and B3 in Fig. 2 as an example, the data in their correlation plot are distributed along a line that slopes upward to the right. Table 2 shows that the correlation coefficient is 0.84, indicating a strongly positive

correlation.

Indices A3 and B3 serve as indices for appropriateness of vehicle response to steering and that of yaw response, respectively. The correlation suggests that, despite such

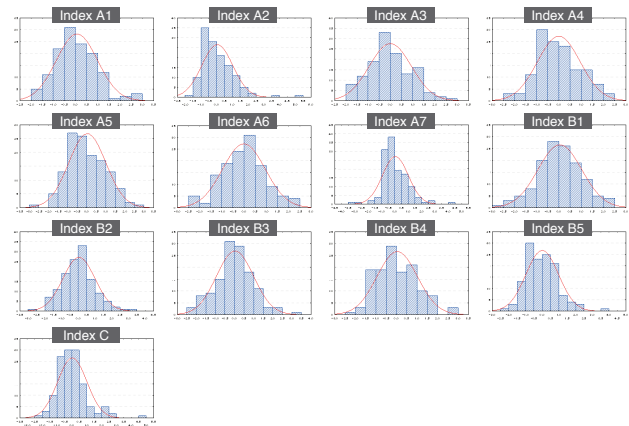


Fig. 1 Statistical distributions of handling indices

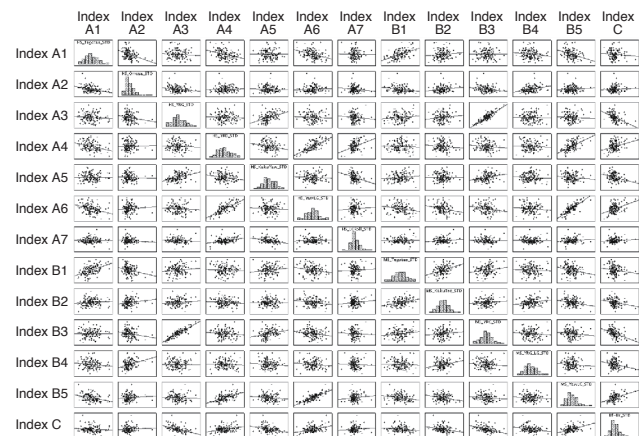


Fig. 2 Overview of correlations among handling indices

Table 2 Covariance matrix of handling indices

	Index A1	Index A2	Index A3	Index A4	Index A5	Index A6	Index A7	Index B1	Index B2	Index B3	Index B4	Index B5	Index C
Index A1	0.88	-0.34	-0.07	-0.30	0.00	-0.34	-0.02	0.47	0.09	0.00	-0.13	-0.32	-0.08
Index A2	-0.34	0.98	-0.18	0.04	-0.05	0.08	-0.12	-0.24	0.16	-0.19	0.33	0.09	0.07
Index A3	-0.07	-0.18	0.91	-0.04	0.39	-0.06	-0.08	0.12	0.12	0.84	-0.02	-0.06	-0.48
Index A4	-0.30	0.04	-0.04	0.95	-0.22	0.70	0.36	-0.05	-0.09	-0.10	-0.05	0.55	0.30
Index A5	0.00	-0.05	0.39	-0.22	1.01	-0.06	-0.34	0.14	0.00	0.26	-0.09	-0.11	-0.31
Index A6	-0.34	0.08	-0.06	0.70	-0.06	0.96	0.07	-0.21	-0.21	-0.19	-0.10	0.77	0.38
Index A7	-0.02	-0.12	-0.08	0.36	-0.34	0.07	1.01	0.05	0.12	-0.05	-0.04	0.12	0.09
Index B1	0.47	-0.24	0.12	-0.05	0.14	-0.21	0.05	1.01	0.35	0.18	-0.05	-0.23	-0.16
Index B2	0.09	0.16	0.12	-0.09	0.00	-0.21	0.12	0.35	0.98	0.12	0.24	-0.23	-0.25
Index B3	0.00	-0.19	0.84	-0.10	0.26	-0.19	-0.05	0.18	0.12	0.98	-0.09	-0.11	-0.42
Index B4	-0.13	0.33	-0.02	-0.05	-0.09	-0.10	-0.04	-0.05	0.24	-0.09	1.00	-0.09	-0.24
Index B5	-0.32	0.09	-0.06	0.55	-0.11	0.77	0.12	-0.23	-0.23	-0.11	-0.09	0.98	0.43
Index C	-0.08	0.07	-0.48	0.30	-0.31	0.38	0.09	-0.16	-0.25	-0.42	-0.24	0.43	1.00

differences in evaluation conditions as speed and driving mode, both of these indices can be explained by common factors.

In contrast, Index C, the appropriateness of understeer, is related to directional stability and has negative correlations of -0.48 and -0.42, respectively, with Indices A3 and B3, which are indices of vehicle responsiveness as mentioned earlier. These results suggest that there is a trade-off between the indices of vehicle responsiveness and stability, and that individual indices may represent different aspects of the factor governing stability.

Thus, the relationships presented in Fig. 2 and Table 2 reveal relatively strong positive or negative correlations among multiple indices, confirming the possibility that common latent factors exist behind this group of evaluation indices.

Since factor analysis is a statistical analysis method that assumes the existence of a correlation structure among the various indices, it cannot be applied to uncorrelated data. Next, the existence of this correlation was examined.

2.4. Bartlett's Test of Sphericity

Bartlett's Test of Sphericity is the standard test method for determining the statistical significance of correlations between evaluation indices⁽⁶⁾.

This test examines the null hypothesis that all evaluation indices are uncorrelated, and have equal variances, and that the correlation matrix $\mathbf{R}$ is the identity matrix $\mathbf{I}$, i.e. the test statistic χ^2 is zero. If this null hypothesis is rejected, it indicates significant correlations between evaluation indices, providing statistical support for the validity of applying factor analysis.

This test was conducted using the 13 evaluation indices for 129 out of 140 vehicles shown in Table 1, excluding samples containing missing values. The results are shown in Table 3.

The n in the table represents the number of samples (=129), m is the number of evaluation indices (=13), and $\mathbf{R}$ is a matrix whose elements are correlations between evaluation indices.

Table 3 Bartlett's test of sphericity

Test statistic*	$\chi^2 = -\left(n - 1 - \frac{2m+5}{6}\right) \ln \mathbf{R} = 780.03$
Degrees of freedom	df = m(m-1)/2 = 78
p value	p = 0.000 < 0.001

The test statistic χ^2 was 780.03, a very large value, and the p-value for the null hypothesis that all indices are uncorrelated was less than 0.001 with 78 degrees of freedom. Therefore, the null hypothesis was rejected, demonstrating statistically significant correlations between indices.

2.5. Cluster Analysis

Next, to gain a qualitative understanding of the general semantic groupings among the indices, a cluster analysis was conducted on the 13 indices, with the results shown in the dendrogram in Fig. 3. Cluster analysis is a method that incrementally groups indices with similar characteristics based on their similarity, and a dendrogram is a tree-like diagram that represents these similarities.

The vertical axis in Fig. 3 lists the 13 evaluation indices, while the horizontal axis represents the Euclidean distance between them. Euclidean distance represents the straight-line distance between evaluation indices when they are plotted as points in a multidimensional space, with smaller values indicating greater similarity in behavior between the indices.

This dendrogram shows that the evaluation indices can be broadly classified into two clusters. Below is a semantic interpretation of these clusters.

In the upper cluster, Index A3, which evaluates the appropriateness of the vehicle's response to steering input, and Index B3, the appropriateness of yaw response,

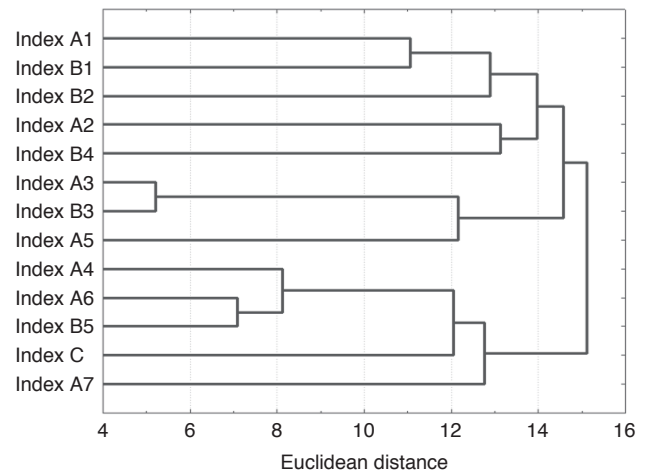


Fig. 3 Dendrogram calculated by nearest neighbor method

are linked at the shortest distance, while Index A5, responsiveness to steering input, joins this cluster at the next shortest distance. These are indices of vehicle behavior in response to steering input, and this cluster can be categorized as “a group of evaluation indices related to vehicle behavior.”

In contrast, Index A1, which represents the steering feedback quality, Index B1, the steering torque at cornering turn-in, and Index B2, optimal steering effort at turn-in are also closely clustered together, which can be interpreted as a cluster of “steering feel” perceived by the driver.

On the other hand, in the lower cluster, Index A4, response linearity to steering input, Index A6, rear-axle response fidelity to steering input, and Index B5, front-axle response fidelity to steering input, are closely clustered. Although this group of indices is related to handling and stability, compared to the indices group of Index A3, B3, and A5 that relate directly to vehicle dynamic response, they can be understood as subjective evaluations that emphasize “consistency with driver intent.”

These examples suggest that even indices that appear to evaluate the same aspect of handling and stability may differ in their underlying evaluation perspectives and latent characteristics. These results qualitatively demonstrate that the subjective evaluation of handling and stability has a multifaceted structure, and that factor analysis may enable the structure to be systematically organized into a quantitative factor model.

3. Factor Models

3.1. Factor Analysis

Based on the qualitative analysis above, a factor model was constructed to quantitatively describe handling and stability.

Specifically, as shown in Eq. (1), the deviation $x_j - \mu_j$ from the mean value of the evaluation index x_j is modeled as the sum of a linear combination of common factors f_k and factor loadings λ_{jk} , and a unique factor ε_j .

$$\begin{aligned} x_j - \bar{x}_j &= \lambda_{j1}f_1 + \lambda_{j2}f_2 + \cdots + \lambda_{jm}f_m + \varepsilon_j \quad (j=1,2,\dots,k) \\ \therefore \mathbf{x} - \boldsymbol{\mu} &= \mathbf{\Lambda}\mathbf{f} + \boldsymbol{\varepsilon} \end{aligned} \quad (1)$$

Where,

$\bar{x}_j = E[x_j]$, $E[f] = 0$, $\text{Var}[f] = \Phi$, $E[\varepsilon] = 0$, $\text{Var}[\varepsilon] = \Psi$,
m: number of common factors, j: evaluation index number, k: total number of evaluation indices

Here, factor loading represents the influence of a common factor on each evaluation index. This is important for interpreting the meaning of the extracted latent factors. In other words, evaluation indices with similar factor loading values are interpreted as sharing underlying common latent factors.

The variance-covariance matrix Σ of the observed variables can be expressed as in Eq. (2) using the above-calculated factor loading matrix Λ , the variance matrix Φ

of the common factors, and the variance Ψ of the unique factors.

$$\Sigma = \text{Var}[\mathbf{x}] = E[(\mathbf{x} - \boldsymbol{\mu})(\mathbf{x} - \boldsymbol{\mu})^T] = \mathbf{\Lambda}\Phi\mathbf{\Lambda}^T + \Psi \quad (2)$$

This relationship means that the observed variance $\text{Var}[\mathbf{x}]$ can be deconstructed into a component $\mathbf{\Lambda}\Phi\mathbf{\Lambda}^T$ explained by common factors and a component Ψ explained by unique factors. The proportion explained by the common factors is called the cumulative explained variance. Generally, a cumulative explained variance of 70% or higher is considered to provide sufficient explanatory power for practical purposes.

In factor analysis, to facilitate the factor interpretation based on factor loadings, a mathematical operation to rotate the factor axis is performed, as illustrated in the schematic image in Fig. 4, before the interpretation.

This research assumed independence among the factors and applied varimax rotation, a type of orthogonal rotation method. After the factor rotation, the number of factors that could best explain the phenomenon was selected exploratorily and factor interpretation was conducted to assign meaning to each factor.

3.2. Selection of Number of Factors

In factor analysis of subjective evaluations, it is important that the statistically extracted factors can be reasonably interpreted as human subjective evaluations. Next, to determine the number of factors needed to appropriately represent the subjective evaluation structure for handling and stability, an exploratory study was conducted in which the number of factors was varied.

Using data from the 129 vehicles, excluding samples containing missing values, factor analysis was conducted for the 13 indices shown in Table 1, with a varying number of factors from two to nine. The Eigenvalue threshold was set at 0.2 as the criterion for factor extraction, and varimax rotation was applied to each case. For the statistical analysis, STATISTICA from TIBCO Software Inc. was used.

When the number of factors was two or three, several evaluation indices did not show high factor loadings on any of the factors, and a sufficient evaluation structure for handling and stability could not be obtained.

In contrast, when the number of factors was six or more, single-indicator factors appeared, i.e. factors where only a single evaluation index exhibited a high loading, and a tendency toward over-segmentation of the evaluation

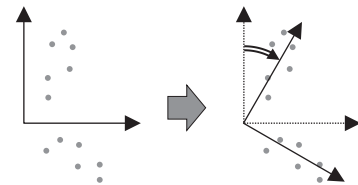


Fig. 4 Schematic image of factor axis rotation

Table 4 Comparison of factor models of handling indices

2 Factor	3 Factor	4 Factor	5 Factor	6 Factor	7 Factor	8 Factor	9 Factor								
Four factor model					Five factor model					Six factor model					
Handling Index	Factor 1	Factor 2	Factor 3	Factor 4	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Index A1	-0.50	0.12	-0.59	0.26	-0.41	-0.16	0.37	0.64	-0.01	-0.37	-0.14	-0.19	-0.76	-0.01	0.08
Index A2	0.04	0.18	0.77	-0.05	0.11	-0.22	-0.73	-0.24	-0.19	0.05	-0.24	0.65	0.49	-0.19	-0.20
Index A3	0.03	-0.96	-0.03	0.00	0.02	0.96	0.02	0.03	-0.10	0.02	0.96	0.01	-0.01	-0.10	-0.01
Index A4	0.85	0.04	0.01	0.25	0.83	0.00	-0.03	0.01	0.34	0.84	0.00	0.03	0.01	0.33	-0.02
Index A5	-0.19	-0.54	-0.04	-0.39	-0.01	0.41	0.04	0.14	-0.70	-0.01	0.41	0.04	-0.12	-0.70	0.08
Index A6	0.88	0.07	0.03	-0.12	0.93	-0.09	0.03	-0.11	-0.04	0.93	-0.09	-0.07	0.12	-0.05	0.04
Index A7	0.34	0.12	-0.13	0.64	0.16	0.03	0.04	0.09	0.85	0.15	0.03	0.07	-0.07	0.86	0.06
Index B1	-0.26	-0.18	-0.41	0.54	-0.07	0.11	0.05	0.90	-0.02	-0.05	0.12	0.25	-0.87	-0.03	0.03
Index B2	-0.25	-0.18	0.29	0.67	-0.13	0.15	-0.58	0.56	0.16	-0.16	0.15	0.79	-0.31	0.16	-0.16
Index B3	-0.04	-0.89	-0.12	0.06	-0.08	0.91	0.10	0.05	0.00	-0.10	0.91	0.02	-0.03	0.01	0.11
Index B4	-0.17	0.01	0.70	0.26	-0.14	-0.01	-0.75	-0.06	0.07	-0.04	-0.06	0.16	0.08	0.00	-0.94
Index B5	0.85	0.07	0.02	-0.13	0.86	-0.08	0.06	-0.17	0.00	0.86	-0.08	-0.07	0.17	0.00	0.09
Index C	0.44	0.61	-0.19	-0.15	0.44	-0.61	0.25	-0.08	0.05	0.39	-0.60	-0.01	0.10	0.08	0.44
Variance contribution	0.23	0.19	0.14	0.12	0.21	0.18	0.13	0.13	0.11	0.20	0.19	0.09	0.13	0.11	0.09
Cumulative contribution	0.23	0.42	0.56	0.68	0.21	0.40	0.52	0.65	0.76	0.20	0.39	0.48	0.61	0.72	0.81

indices was observed. Such a factor structure is not only a challenge to interpret but is also considered highly sample-dependent, which may reduce the generalizability of the evaluation structure.

Considering the above, factor interpretations were performed on the cases with four or five factors, where multiple evaluation indices showed high factor loadings and factor interpretation was relatively clear. Also, a six-factor model in which a single-indicator factor appeared was also discussed for reference.

3.3. Four-Factor Model

Table 4 compares the factor loadings, the variance contribution of each factor, and the cumulative explained variance for the 13 evaluation indices when the number of factors is set to four, five, or six.

Looking at the four-factor model on the far left, Factor 1 exhibits high factor loadings for Indices A1, A4, A6, and B5, suggesting that this factor is related to steering feedback quality, response linearity to steering input, rear-axle response fidelity to steering input, and front-axle response fidelity to steering input. Therefore, Factor 1 in the four-factor model is interpreted as the “steering feel and vehicle dynamic response” factor.

Factor 2 exhibits high factor loadings for Indices A3, B3, A5, and C, and is related to vehicle steering response, yaw-rate response, responsiveness to steering input, and the appropriateness of understeer. In general, theoretically the greater the understeer, the smaller the phase lag of the steering response below the resonance frequency,

and the faster the response becomes. Factor 2 can thus be interpreted as a “degree of understeer” factor.

Factor 3 contributes strongly to Indices A1, A2, and B4, and is related to steering feedback quality, steering torque during high-speed turn-in, and linearity. It can therefore be interpreted as a “steering feel” factor.

Factor 4 exhibits high factor loadings for Indices A7, B1, and B2, and is related to perceived cohesion of vehicle behavior, steering torque at cornering turn-in, and appropriateness of steering effort at turn-in. It is therefore considered to be a “sprung-mass behavior and steering feel” factor.

The cumulative explained variance of this four-factor model is 68%, indicating that slightly less than 70% of the total evaluation indices can be explained with just four factors.

3.4. Five-Factor Model

In the five-factor model shown in the middle part of Table 4, the allocation of evaluation indices to each factor became clearer compared to the four-factor model.

Factor 1 in the five-factor model was derived by separating Index A1 from the four-factor model. Factor 1 consists solely of indices directly related to vehicle dynamic response, namely response linearity to steering input, rear-axle response fidelity to steering input, and front-axle response fidelity to steering input, and can therefore be interpreted as a “vehicle dynamic response” factor.

Similarly, Factor 2 was derived by separating Index A5, responsiveness to steering input, from the four-factor model

Table 5 Five factors and their interpretations

Factor	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Subjective evaluation term	"Response Linearity to Steering Input"	"Appropriate Vehicle Response to Steer"	"Steering Torque at High Speed Turn"	"Steering Torque at Cornering Turn-In"	"Responsiveness to Steering Input"
	"Rear-Axle Response Fidelity to Steer"	"Appropriateness of Yaw Response"	"Optimal Steering Effort at Turn-In"	"Steering Feedback Quality"	"Perceived Cohesion of Vehicle Behavior"
	"Front-Axle Response Fidelity to Steer"	"Appropriateness of Understeer"	"Linearity in Steering Response"	"Optimal Steering Effort at Turn-In"	
Factor interpretation	<Vehicle Dynamics>	<Understeer>	<Steering Feel>	<Steering Effort and Torque>	<Integrated Vehicle Behavior>
Contribution	21%	18%	13%	13%	11%

and consists of the appropriateness of vehicle response to steering, appropriateness of yaw-rate response, and appropriateness of understeer, and is clearly interpreted as a "degree of understeer in a quasi-steady state" factor.

Factor 3 exhibits high factor loadings for Indices A2, B2, and B4 and thus is related to steering torque at high-speed turn-in, optimal steering effort at turn-in, and linearity, and can be interpreted as a "steering feel" factor.

Factor 4 exhibits high factor loadings for Indices A1, B1, and B2 and thus is related to steering feedback quality, steering torque at cornering turn-in, and optimal steering effort at turn-in. It is therefore reasonable to explain it as a "steering torque and steering effort" factor.

Factor 5 exhibits high loadings for Indices A5 and A7 and thus is related to responsiveness to steering input and perceived cohesion of vehicle behavior, and can be interpreted as a "driver-vehicle unity" factor.

In this five-factor model, the conceptual consistency of each factor has been further enhanced, and the cumulative explained variance reaches 76%, which exceeds the 70% threshold generally considered to indicate a sufficiently convincing factor model.

3.5. Six-Factor Model

A six-factor model was also tested as part of exploring the number of factors. Here, Factors 1, 2, and 5 have the same structure as in the five-factor model, allowing for a consistent interpretation of these as fundamental factors. For Factors 3 and 4, however, the factor structure that had been consolidated in the five-factor model was overly fragmented, resulting in Index B4, linearity in steering response, emerging as a single-indicator factor as Factor 6.

Regarding Factor 4, Index B2, the appropriateness of steering effort at turn-in, was separated from the "steering torque and steering effort" of the five-factor model, revealing a tendency for conceptually adjacent evaluation indices to be over-segmented.

Factor analysis is a method that uses correlations between observed variables as a basis to explain variations with a small number of common latent factors. For this reason, the presence of a single-indicator factor, i.e. a factor consisting of a single evaluation index, indicates that a structure that could be consolidated is fragmented. This

is undesirable and could lead to a high degree of sample dependence. In other words, a single-indicator factor is highly unlikely to be an underlying, intrinsic latent factor.

Although this six-factor model shows a cumulative explained variance of 81%, which is five points higher than that of the five-factor model, it could be judged inappropriate for use as a factor model for representing the factor structure of handling and stability due to over-segmentation of the evaluation indices and the presence of a single-indicator factor.

3.6. Factor Model Structure Interpretation

Figure 5 summarizes the variance contribution of each factor when the number of factors is varied from two to nine.

Based on the results from Sections 3.1. through 3.5. and considering that the five-factor model has the highest contribution of any factor structure shown in Fig. 5 without a single-indicator factor, the five-factor model, which had a cumulative explained variance of 76% and provided clear interpretations of the meaning of each factor, is concluded to be the most appropriate structure for evaluating handling and stability.

Table 5 summarizes the adopted five-factor model and the factor structure with the 13 evaluation indices.

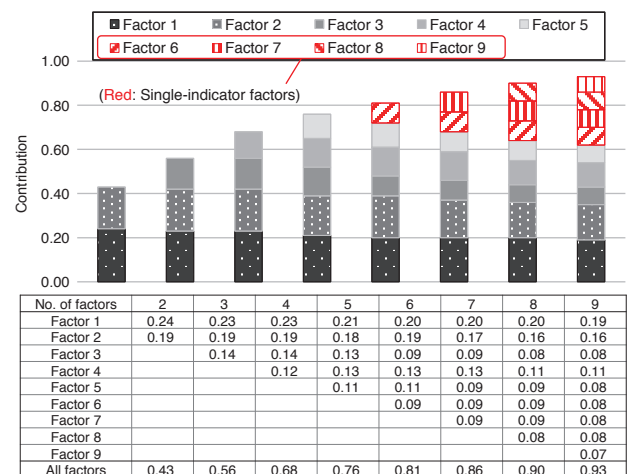


Fig. 5 Number of factors vs cumulative contribution

To summarize the factor interpretation, Factor 1 “vehicle dynamic response,” with a contribution of 21% and Factor 2 “degree of understeer in a quasi-steady state,” with a contribution of 18%, can be considered the primary factors explaining approximately 40% of the vehicle’s handling and stability.

Furthermore, Factor 3 “steering feel” and Factor 4 “steering torque and steering effort” both have a contribution of 13%. They are secondarily important factors after the primary ones and constitute steering feel in the broad sense.

Although Factor 5 “integrated vehicle behavior” makes a relatively small contribution of 11%, it is considered, together with Factors 1 and 2, to be a factor that complements a different aspect of vehicle behavior evaluation.

Figure 6 schematically illustrates the relationship between these five factors and the 13 evaluation indices used in practice. The factor structure shown in this figure is consistent in many respects with the cluster analysis results presented in the previous chapter, confirming that the latent evaluation structure underlying the handling and stability indices has been systematically organized.

This organization of the factor structure demonstrates that the group of 13 evaluation indicators can be categorized into five perspectives. This allows evaluators to understand the relationships among numerous evaluation indices from the perspective of common latent factors, enabling them to use this information to identify the evaluation areas to prioritize for each vehicle concept.

4. Conclusion

This research applied factor analysis to the 13 evaluation indices used to evaluate handling and stability and obtained the following findings.

- (1) The proposed five-factor model can explain 76% of the variance in the 13 evaluation indices for handling and stability.
- (2) By using this model, the relationship between factor scores and evaluation indices can be expressed by Eq. (1). This enables the identification of which factors have the strongest influence on each evaluation index, while also enabling as well as the use of factor scores as indicators for understanding the handling and stability evaluation structure.
- (3) By referring to the variance contribution of each factor considering the vehicle concept and evaluation objectives, it is possible to identify the characteristics to prioritize in terms of handling and stability.

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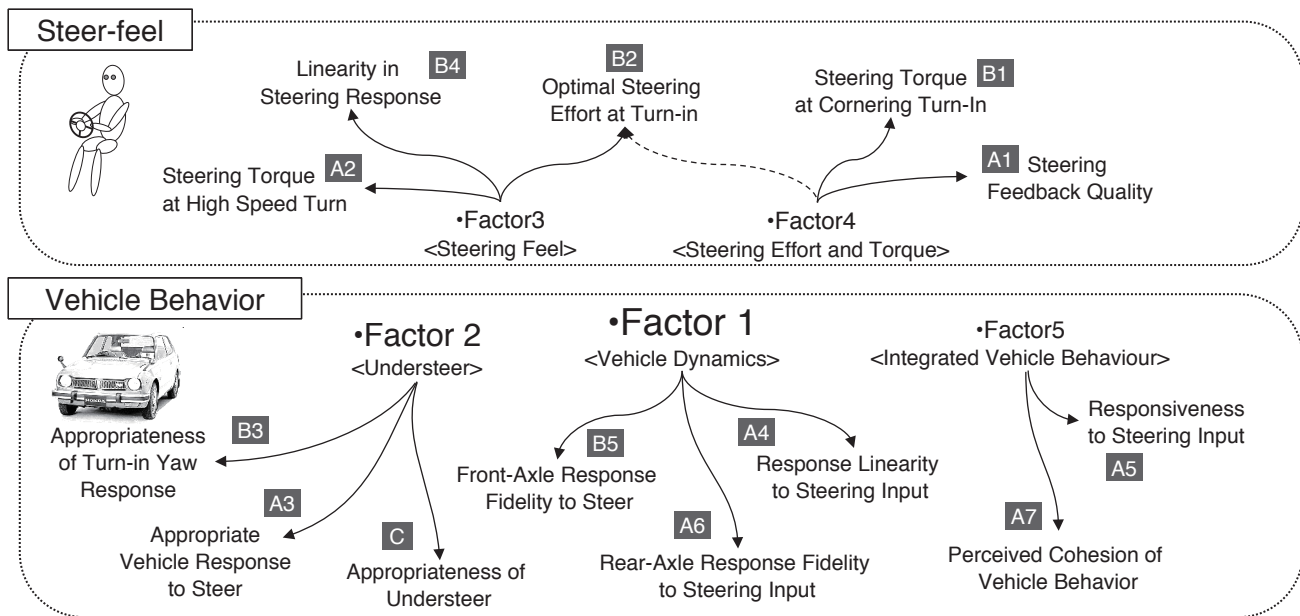


Fig. 6 Five factors and related subjective evaluation terms

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