Quantifying Roll Feel of a Vehicle by Measurement of Driver’s Body Motion

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ABSTRACT: This paper presents a study to quantify the difference in roll feel experienced by the driver with a change in damper characteristics between “comfort” and “sport” mode. The vehicle and driver’s motion are measured during the double lane change maneuver. In “sport” mode, the timing of steering operation was found to be faster (P = 0.0456), which can be explained by the driver being able to make quick upper body corrections to resist the slow vehicle roll motion. This difference in steering operation because of the man-machine feedback system can be considered as an objective measure to quantify roll feel.

KEY WORDS: Vehicle Dynamics, Electronically Controlled Suspension System, Driver Model, Motion Control, Roll Feel (B1)

1. Introduction

According to a recent survey on automobile ownership (1), the top five requirements related to automobiles are "ease of driving", "comfort", "safety and security", "good fuel economy", and "style-design". It was also found that the so-called vehicle dynamic performance including "safety and security" are ranked higher and are of greater consumer interest, reflecting the fact that the improvement in durability and fuel efficiency has been technically completed.

The performance of automobiles that need to comfortably carry occupants to their destination has been traditionally evaluated based on human dynamics (2) that take human characteristics into consideration. In addition, turning motion and direction-change by steering operation are the essential functional requirement of automobiles that can move freely regardless of the restraint of the track, etc. The accompanying roll behavior has also attracted a lot of interest and many examples of such studies are available (3).

It is empirically known that the transient roll behavior when turning has a great influence on the steering feel. Due to the steering operation of the driver, since the roll motion occurs along with the turning of the vehicle, the driver strongly feels the good or bad of the roll feel as a sensory value together with the steering feel. For this reason, although transient roll behavior is not a major factor in vehicle turning performance (i.e., in terms of generation of yaw movement), many roll-feel related studies have been conducted with the aim of improving "ease of driving" and "safety and security". For example, Muragishi et al.; Yamamoto et al.; Kodaira et al. (4-6) showed from the subjective assessment results that a good feel is achieved during slalom driving by having no phase difference between the roll and pitch angle of the vehicle, the so-called "nose down roll". Buma et al. (7) measured the movement of the driver's head during steering and showed that the head was actively moving against the roll motion of the vehicle. Yamaguchi et al. (8) showed that the difference in the holding ability of the seat affects the roll feel. Trivedi et al. (9) showed that the roll feel differs not on the absolute magnitude of the roll angle but depends on the distance between the driver's seating position and the roll axis. Yoshioka et al. (10) mentioned that the difference in G-Vectoring Control (GVC) could cause a difference in the roll-pitch related vehicle posture and depending on the closed-loop of the driver-vehicle system, the steering operation also differs. In addition, to examine "ride comfort" in anticipation of the era of autonomous driving, a method has been proposed in which the passenger is modelled using spring-damper system to evaluate the roll behavior of vehicle (11).

In this way, research on roll feel began with the correlation between vehicle characteristics and subjective evaluation. It gradually moved to analyzing both vehicle performance and driver behavior, where coupled planar and roll motion of vehicle with steering actuation by driver are considered to study as a man-machine system. The need to accurately perform controlled
experiments involving human operations, and to keep the test conditions consistent, has ramped the use of a driving simulator (DS) to supplement actual vehicle tests. A research example based on the recognition of the same problem that the environmental factors are uneven, and the analysis from the actual vehicle test is difficult, has shown the validity of the DS test using statistical analysis (12). It is thought that DS will substitute the actual vehicle test more and more in the future. However, when examining subjective perceptions such as good or bad roll feel, there is a concern that minute differences between the DS and the actual vehicle may considerably affect the analysis results, so at present the DS tests are still predominantly utilized in analyzing human steering response characteristics, etc. In addition, since the roll feel is perceived including the pitch behavior, 6-degrees of freedom DS is required for analysis, and such a large-scale DS facility is another issue.

From these backgrounds, in this study, the authors report the attempt to quantify the roll feel during steering with change in suspension damping force characteristics of the vehicle. To directly feel the roll feel during steering and to ensure measurement accuracy, actual vehicle test was performed twice in two-stages.

2. Test Procedure

Since the roll feel when driving on the road depends on both the steering operation and the change in roll attitude, the closed-loop test is more appropriate instead of the open loop. Therefore, a test road that regulated the driving course was chosen. An expert, proficient in tuning of the actual vehicle was appointed as a driver. The outline of the test, the contents of the data to be measured, etc. were shared well before the test and informed consent was obtained.

2.1 Test Course

As a closed-loop test, a double-lane change course conforming to ISO3888-2 was selected. The vehicle was set to run at a constant speed to ensure that there is no restriction to the steering wheel operation from driver’s point of view. Fig.1 shows the outline of the test-course.

2.2 Test Vehicle and Damper Characteristics

The actual test was carried out using a hatchback type C category, left-hand steering vehicle, with weight = 1348[kg], wheelbase = 2.635[m], front tread = 1.520[m], and rear tread = 1.500[m]. The test vehicle was installed with a variable damper system whose damping force characteristic can be adjusted by change in the current applied to the solenoid valve. The damping force characteristics were tuned by multiple iterations of actual running test so that the subjective comments related to the feeling could be recorded accurately. Finally, the actual vehicle was equipped with two modes of damper setting, "comfort", which favors ride comfort, and "sport", favoring maneuverability. The two modes do not involve any specific control logic, in other words, the applied current was fixed, and suspension system was made to behave as a "Conventional Damper". Fig.2 shows the characteristics of the selected two modes of damper.

3. Experiment (Stage I)

3.1 Measured Variables

Broadly categorizing, the measured variables are of two types, one related to the physical quantity of the vehicle and the other related to the physical quantity and myoelectricity of the driver behavior. Specific measurement items are summarized in Table 1.

Fig.3 shows the vehicle’s coordinate system. Sensor quantities are expressed in ISO right-hand coordinate axes with the x-axis pointing forward from the vehicle and the z-axis pointing vertically up from the ground. Fig.4 shows the coordinate system used for variables related to driver. The driver’s coordinate system moves along with the driver and coincides with that of vehicle’s when the vehicle is standing still. Moreover, the mounting positions of the sensors affixed to driver are also shown in Fig.4. 6-axis inertial measuring unit (IMU) was attached both to the trunk and head to measure the movement of the driver’s upper-half body during steering. Simultaneously, a camera was also attached to the head to record the visual information outside the windshield as seen by the driver while driving, and for
reference, the images from dashboard-mounted camera were utilized for the analysis of driver's movement. The muscles that are dominantly active in steering wheel operation and those that help to maintain a stable sitting position were selected to measure myoelectric potential using electromyography (EMG) as described in Table 2. A 13-channel amplifier, 6 for left-side muscles, 6 for right-side muscles and 1 for reference signal, with bandpass (30-3000[Hz]) filter was used to avoid to antialiasing effects within sampling. To build a musculoskeletal mathematical model, reflective markers were attached to the appropriate parts of the driver's upper body, and infrared cameras were attached to the feasible location in the test vehicle to capture the reflection of the above reflective markers. A pressure sensing mat was installed on the driver’s seat surface to measure the weight shift of the driver during steering. Fig.5 shows the setup of these measuring instruments and sensors inside the test vehicle.

| Items          | Setup Location                  |
|----------------|---------------------------------|
| Vehicle Speed  | Vehicle CAN                    |
| Steer Angle    | Vehicle CAN                    |
| 6-axis IMU     | Near center of gravity         |
| Camera         | Above dash-board               |
| Motion Capture System | Essential locations to build musculoskeletal model |
| EMG            | Upper body muscles (Table 2)   |
| Pressure Sensing Mat | Driver’s seat                 |
| 6-axis IMU     | Trunk and head (Fig.3)         |
| Camera         | Head (Fig.3)                   |

### Table 2 Muscles Measured using EMG

| Muscle Name                 | Symbol |
|-----------------------------|--------|
| Trapezius Muscle            | T      |
| Deltoid Muscle              | D      |
| Biceps Brachii              | BB     |
| Triceps Brachii Long head   | TBL    |
| Latissimus Dorsi            | LD     |
| Pectoralis Major            | P      |

#### 3.2 Pre-Processing

For each test run, the time axes of all the measured variables were aligned using the reference signal (square wave of 5[V]), which was sent to all the measuring devices. On the other hand, the time axis of all the independent trials of the test run were aligned using time delay calculated by the lag at which the cross-correlation between each pair of steer angle signals has the largest absolute value.
3.3 Test Results

The constant vehicle speed at which the instantaneous peak lateral acceleration is about 8[m/s²] (≈ 0.8g), 50[km/h], was selected as one of the speed patterns for the test. In addition, two different speeds below 50[km/h], viz, 40[km/h] and 30[km/h] were selected to have total 3 levels of speed variation. Three trials of test were conducted for each mode (sport and comfort) of damper. Before each trial, the driver was informed in advance about the damper mode. In the following analysis, the results of a vehicle speed of 50[km/h], wherein variations were large, are described.

Fig.6 shows the vehicle and driver’s head and trunk yaw behavior. The yaw motion of trunk is almost in unison with that of vehicle, but the head seems to move actively to obtain visual information in front of the vehicle. Fig.7 shows that the roll rate of vehicle tends to be smaller in sport mode as compared to comfort mode. On the other hand, as described in reference (7), it can be confirmed that the head rolls opposite to the roll motion of vehicle. At the same time, the result of the IMU attached to the trunk shows that not only the head but the entire upper body is resisting the roll motion. The correction for this behavior seems to be smaller in sport mode than comfort mode. The same can also be confirmed from the pressure distribution of the driver’s seat. An example of one measurement of pressure distribution is shown in Fig.8. Specifically, the variation of the center of pressure (CoP) along the lateral direction obtained from the measured pressure distribution, as shown in Fig.9, suggests that comfort mode has a larger fluctuation range and, hence more body movement than sport mode. Also, the absolute value of the net seat force decreases during the steering operation, which can be possibly explained by the transfer of upper body load to the legs, seat backrest, or the steering wheel.

In addition, the data measured by motion capture was used to build the rigid-body link model and the musculoskeletal mathematical model, as shown in Fig.10. From the results of model analysis, presented in detail in a separate conference (13,14), it was found that the amount of rotational drive power used in neck muscles is smaller in sport mode than in comfort mode, suggesting that sport mode has less burden to support the driver’s upper body.
Furthermore, from the relation between activation of EMG signal and variation in steer angle, the function of various muscles in relation to steering operation can be obtained. As shown in Fig. 11, both persistent potential (low amplitude) and phasic (large amplitude) muscle activity are present in pectoralis major muscle. The phasic muscle activity (up arrow) corresponds to the onset of steering angle change. Its amplitude and duration correspond to the magnitude of the change in steering angle. This fact is consistent with the functions of the pectoralis major muscle: the stability of the body axis of the pectoralis major muscle and the adduction of the shoulder joint. In other words, the pectoralis major plays a role both in stable control of the upper body and in steering movement.

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From the results of the above analysis on both physical and physiological variables, there is a difference in the roll rate of the vehicle during double lane change due to the difference in the sport/comfort mode of the damping force characteristics, which tends to be smaller in the sport mode than in the comfort mode. Also, the driver actively moves their trunk and head in the direction against the roll behavior of the vehicle to keep themselves parallel to the ground. Although not shown, the images from the dashboard camera and the camera attached to the driver’s head reveals that the driver’s head-mounted camera has a larger motion than the one on dashboard. Therefore, to quantify the roll feel, it is necessary to evaluate both the vehicle and the driver together as a system.

In view of this, to analyze the behavior of vehicle and driver as a system in detail, the authors decided to repeat the same test by increasing the number of trials with statistical analysis in mind.

4. Experiment (Stage II)

4.1 Measured Variables

From the measurement items in Table 1, focus was on physical values other than camera for vehicle and the two 6-axis IMUs only for driver. The test was conducted using the same test vehicle and test course as last time, but vehicle speed was limited to one pattern only, i.e., 50[km/h]. Also, with statistical analysis in mind, the number of trials was set to 15 for each mode (sport and comfort). During the test, to avoid any bias, the driver was not told anything before each trial about the damper mode. Each mode was chosen randomly 15 times each, so a total of 30 test runs were performed by the same driver. After each test run, the driver’s comment about drivability with respect to steering operation and assessment of whether the damping force characteristic was of sport or comfort mode were also noted.

4.2 Statistical Analysis

There are 30 signals of each variable of interest, 15 for each mode (sport and comfort) of damper force characteristics. At any instant of time, the available 30 values corresponding to variable of interest are independent and statistical analysis can be performed on these 30 independent samples. These samples are in 2 independent groups, viz, comfort and sport mode, of 15 samples each. Assuming the samples to be taken from normal populations with unknown but equal variances, a 90% confidence interval (CI) for each group was calculated using Eqn. (1).

\[ CI = \left[ \bar{x} - t_{n-1} \frac{s}{\sqrt{n}}, \bar{x} + t_{n-1} \frac{s}{\sqrt{n}} \right] \]  

where, \( \bar{x} \) : Sample mean  
\( s \) : Sample variance  
\( n \) : Number of samples  
\( t_{n-1} \) : Critical value of student’s t-distribution

The 90% CI at all sampled instants of time was calculated in the similar way. To test the alternate hypothesis of whether there is a significant difference between the means of two groups, and
that difference is unlikely to be caused by sampling error, an unpaired double-sided t-test was utilized.

Fig. 12 Yaw Behavior of Vehicle, Trunk, and Head in Relation to Vehicle Steer Angle

Fig. 13 Roll Behavior of Vehicle, Trunk, and Head in Relation to Vehicle Steer Angle

4.3 Test Results

Fig. 12 and Fig. 13 show the yaw and roll response of vehicle and driver’s trunk and head with respect to steering operation. The steer angle between comfort and sport mode was found to have a delay in the latter half of the steering operation while returning to the original lane, as shown in Fig. 12. The P value of the difference in time at which the steer angle peaks, specifically between t = 4 [s] and t = 5 [s], is 0.0456, which is statistically significant by conventional criteria. The mean time difference (Δt) is 0.040 [s], with the sport mode being the one with the fast timing of steering operation. Because of this difference in steering operation, the accompanying yaw rate of vehicle also occurs earlier (Δt = 0.032 [s], P = 0.0792) in sport mode than in comfort mode. With the sprung mass moving outside the turning direction, steering the vehicle back into the original lane is considered difficult at this stage. In general, it is known empirically that if the steering operation is same, even if there is a difference in damping force, there is no practical difference in yaw rate of the vehicle. The same was confirmed from the simulation results. Fig. 14 shows the yaw rate of vehicle performing double lane change with same steering angle, but with change in damping force. The same comfort and sport mode used during actual-vehicle test was used and it can be confirmed that the difference in damping force do not yield any practical difference in yaw rate but, roll rate obviously differs at encircled points. In contrast, with respect to base case, twice the spring rate of rear end (k_rear = x2) and halve the spring rate of front end (k_front = x0.5) causes a significant difference in yaw rate, as shown by encircled regions in Fig. 15.

Fig. 14 Simulation Results with Change in Damper Characteristics

As shown in Fig. 13, the driver actively corrects the roll motion of upper body against that of the vehicle. This correction behavior was faster both by the trunk and head of the driver in sport mode as compared to comfort mode. It is reasonable to think that the factor that causes this difference is the transient roll behavior of the vehicle, that is, the roll rate. In sport mode, since the roll behavior of the vehicle is sluggish and comparatively damped as opposed to oscillatory motion in comfort mode, it can be inferred that it is easier for the driver to quickly correct the upper body motion in sport mode, corresponding to the roll response of the vehicle.

Table 3 shows the accuracy of the predicted mode of the damping force characteristics by the driver. The correct response percentage is 87% for sport mode, 80% for comfort mode, and 83% for all 30 trials, indicating that the difference in vehicle behavior
can be recognized with a very high accuracy by the driver. Also, the driver commented that compared to comfort mode, sport mode feels more secure and has better vehicle handling performance.

Table 3 Driver’s Assessment of Damper Mode

| Damper Mode | Correct | Incorrect | Total Number | Correct Rate [%] |
|-------------|---------|-----------|--------------|------------------|
| Sport       | 13      | 2         | 15           | 87               |
| Comfort     | 12      | 3         | 15           | 80               |

The driver's detailed comments on the various phases of steering operation are as follows:

- The sport and comfort mode could not be differentiated until passing the course pylon number R3-L3 and steering towards R4-L4.
- In sport mode, vehicle behavior was more stable, steer operation could be performed quickly, and predictability of vehicle behavior was comparatively better.
- In the comfort mode, after steering, the vehicle felt like understeering.

The statistical analysis, which show that there is no difference in steering input during the course-entry phase and that there is a difference when returning to the original lane at the end of the course, with sport mode having faster steer timing than comfort mode, corroborate the driver’s comments. Furthermore, due to the driver’s expert driving skills, it was extremely rare to hit the pylon number R7, but it is extremely difficult to successfully maneuver the vehicle near this point. As a result, even minor differences in vehicle behavior at this point can be easily distinguished by an expert driver.

5. Conclusion

Since, there is no reason to arbitrarily change the steering operation between comfort and sport mode for the driver who was asked to drive the course without any prior information sharing about the damping force characteristics of the vehicle, the obtained quick steering action in sport mode can be attributed to the driver being able to make quick upper body corrections against the roll motion of vehicle which is comparatively slower in sport mode. As known both empirically and even from simulation studies that with the same steering operation, no significant difference can be incurred to the yaw rate of the vehicle by any change in damping force characteristics, so the observed significant difference in the yaw rate of the vehicle is due solely to the above difference in the driver’s steering action. This difference in the yaw behavior of the vehicle can be attributed to a closed-loop of the man-machine feedback system. From a commercial standpoint, the ability to make a difference in yaw rate using a relatively inexpensive and compact variable damper system is extremely valuable among control suspension systems.

In terms of quantifying roll feel, the double lane change test used in this experiment is not within the range of normal driving operation. However, such a high-speed driving operation was chosen in the hopes of clearly identifying a distinguishing metric. A valuable comment from an expert driver about the secure feeling in sport mode with respect to vehicle behavior as compared to comfort mode, can be viewed as an extrapolation of the usual driving regime, and could be linked to the quality of roll feel.

This study will be expanded in the future to find more specific and precise responsiveness indexes considering the man-machine feedback loop as a single system, such as the time delay between steering angle presented in this study, to concretely quantify the roll feel. In the future, a similar test for performing statistical analysis of EMG measurements, the process for achieving both posture maintenance and steering wheel action in relation to the driver's posture, and an examination of the relationship between vehicle and driver posture to quantify the roll feel will be addressed.

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