

Development of Road Friction Coefficient Estimation Logic

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ABSTRACT

The further development of vehicle stability assist (VSA) and other such forms of vehicle dynamics control requires techniques for estimating the road friction coefficient more accurately and in real-time. The present research integrated non-linear tire characteristics data with vehicle side slip angle estimation logic to develop a new estimation logic that is more accurate and has greater response than the conventional logic. The estimation accuracy of this logic was further verified in tests with actual vehicles, thus demonstrating the validity of the developed logic.

1. Introduction

The authors have continued their research on the further development of vehicle stability assist (VSA) performance using vehicle side slip angle (β) estimation, road friction coefficient (μ) estimation, 4-wheel slip (λ) control and tire characteristic data logics^{(1), (2)}. Of these logics, μ estimation logic plays the most important role in providing a more accurate understanding of road surface conditions. This paper discusses the drawbacks of conventional μ estimation logics, and presents details of a newly developed technique for a more accurate, real-time estimation of the road friction coefficient. The validity of this logic has been proven in vehicle tests. In these tests an FR and an on-demand full-time 4WD were run on snow-covered, low- μ wet basalt, and dry asphalt test courses.

2. Issues and Research Goals

As Fig. 1 shows, during turning nonlinear characteristics and road surface conditions cause tire side forces to vary. The higher the tire side slip angle (α) and the lower the road surface μ , the greater the possibility of saturation being reached. This saturation of tire side forces causes the vehicle to deviate from the intended turning path. When this happens,

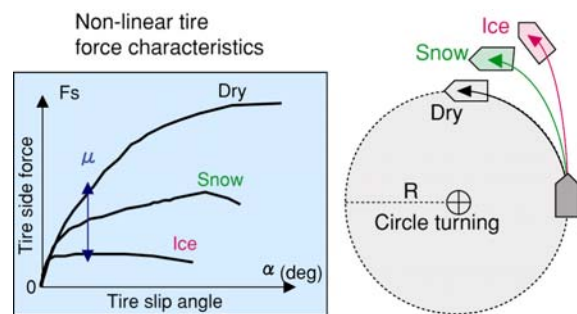


Fig. 1 Tire force characteristic and vehicle dynamics

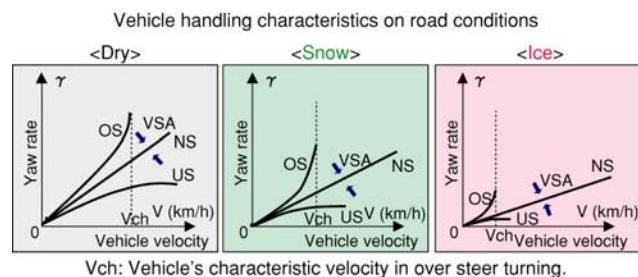


Fig. 2 Vehicle dynamics control

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the grip of the tires becomes uneven and the vehicle behavior becomes unstable, demonstrating oversteer (OS) or understeer (US), as shown in Fig. 2. When driving on icy or snowy road surfaces in particular, tire side forces drop drastically, causing the vehicle to more easily become unstable. This necessitates stability control using VSA or a similar technique. Because the effectiveness of this type of control is related to road surface μ , a μ estimation logic becomes indispensable. The purpose of the research discussed in this paper was to develop a logic to estimate μ to an accuracy of ± 0.05 (μ within a range from 0 to 1, normalized to 1 on dry road surfaces) using steering angle, acceleration and yaw rate sensors.

3. Conventional Road Surface μ Estimation Logics

3.1. μ Estimation Utilizing Slip Rate

This method is the simplest, calculating vehicle acceleration and deceleration and slip rate from acceleration and deceleration of the tires, and taking gain in these values as changes in road surface μ . As shown in Fig. 3, early ABS and traction control systems (TCS) estimated μ indirectly from the relative λ between tires and road surface at braking and during traction, and selected a corresponding control gain. These simple systems used no sensors other than tire speed sensors. Further development was required to enable estimation during turns.

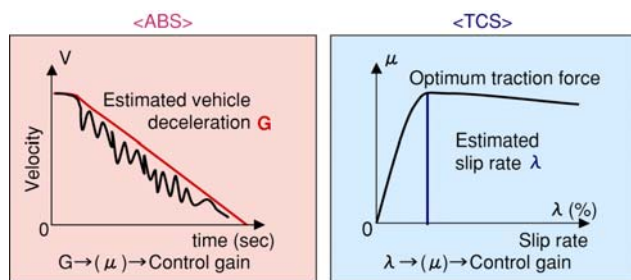


Fig. 3 Primitive slip estimation for ABS and TCS

3.2. μ Estimation Utilizing Yaw Rate

This method adds a steering angle sensor to the system described above. In this system changes in road surface μ are taken as the difference between actual yaw rate and nominal yaw rate (based on a dry road surface) calculated from steering angle and estimated vehicle velocity, providing a logic capable of estimating μ during turns. As Fig. 4 shows,

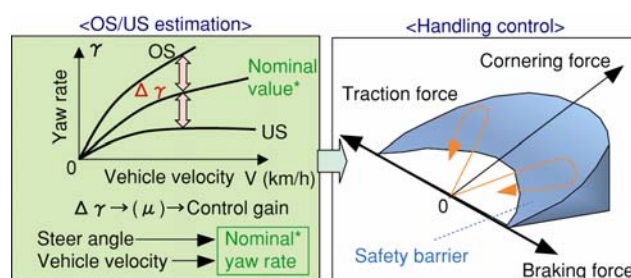


Fig. 4 OS/US estimation for handling control system

this method judges OS and US, making handling control possible. This method makes road surface μ estimation possible during turning with a minimum of sensors and logics, and has enabled performance improvements in ABS, TCS and 4WS. However, there are some drawbacks to this method which require solution: its high level of reliance on steering angle makes it difficult to establish optimum nominal yaw rates for all road surface conditions, and it is particularly difficult to judge OS when the driver contributes excessive steering input in conditions of low road surface μ .

3.3. μ Estimation Utilizing Lateral Acceleration

This method utilizes an acceleration sensor in addition to tire speed and steering angle sensors. Estimation of cornering force (centripetal force) is enabled by finding longitudinal and lateral acceleration. The logic utilized in this method estimates direct μ during turning by regarding the vehicle as one tire and calculating tire gripping force from the friction circle of that tire, as shown in Fig. 5. The estimate of μ provided by this method can be used to correct the steering angle nominal yaw rate found using the previous method, and enables improvement of the accuracy of the nominal yaw rate on icy and snowy roads in particular. However, to maintain a stable level of accuracy of estimation when the tire slip control used by more advanced VSA systems and the like is in operation, the tire gripping force for all four wheels must be calculated separately. This makes a μ estimation method indispensable in combination with tire side slip angle (α) and vehicle side slip angle (β) estimation logics. In addition, tire characteristics are not limited to a simple friction circle; it is essential to increase the accuracy of estimated μ values using nonlinear motive force and side force data corresponding to changes in λ and α .

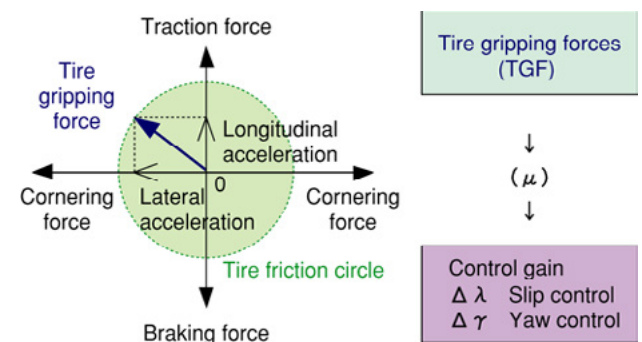
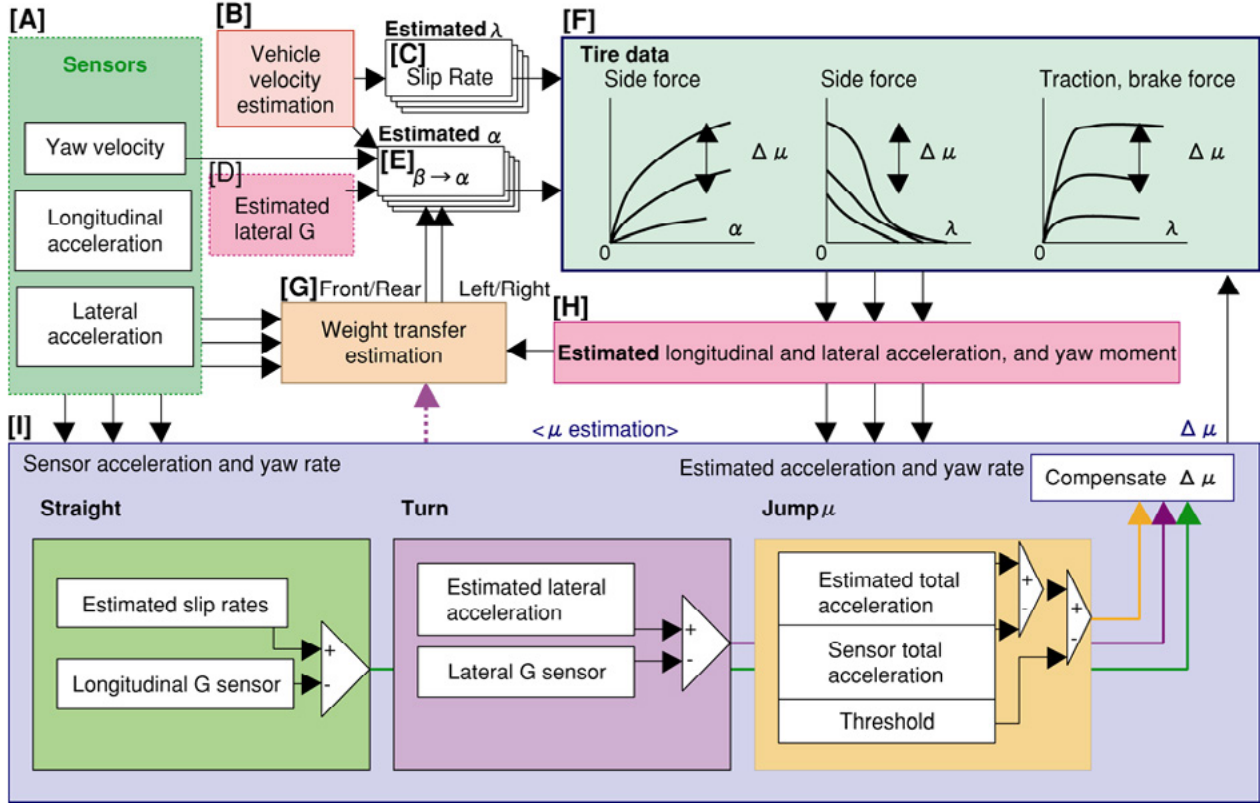


Fig. 5 Estimation of the tire gripping force

4. Newly Developed μ Estimation Logic Utilizing Vehicle Side Slip Angle

To enable road surface μ estimation to be used in vehicle motion control systems like VSA, it was necessary to develop a stable logic which maintained a more accurate target during the operation of λ control. To achieve this, the logic had to estimate α and λ for all four wheels more accurately and in real-time in all conditions, and be able to calculate tire braking and traction force and tire side forces with consideration of dynamic wheel load (F_w).

Figure 6 shows the basic μ estimation logic developed in this project. This logic integrates nonlinear tire characteristic data maps (termed tire data below) reflecting data obtained


 Fig. 6 μ estimation logic

from measurements on actual road and β estimation logic. In addition, it successively corrects the estimated μ values using the three basic parameters of vehicle motion: yaw rate, longitudinal acceleration and lateral acceleration.

Broadly speaking, there are two aspects of this μ estimation logic which are new to these logics. The first of these is that, being combined with a β estimation logic, it estimates yaw rate and acceleration from estimated tire gripping force for each wheel, and provides correction as needed by comparing these estimates with values measured by sensors. The second is that it expresses the basic tire characteristics using nonlinear data reflecting the motion characteristics of actual vehicles.

The remainder of this section will explain the flow of the logic as shown in Fig. 6.

- (1) Vehicle yaw rate, longitudinal acceleration and lateral acceleration ([H]) estimated from β estimates ([D], [E]) and nonlinear tire data ([F]) are compared with the output values obtained from vehicle sensors ([A]) and correction values are calculated.
- (2) These μ correction values are calculated for three driving modes: Straight, turn and jump μ ([I]).
- (3) These μ correction values are applied to the original nonlinear tire data ([F]).
- (4) To maintain the accuracy of vehicle yaw rate, longitudinal acceleration and lateral acceleration estimations during the operation of λ control in VSA and similar systems, tire gripping force is calculated for each wheel ([C], [E], [F]).
- (5) During turning, estimated α is corrected with estimated front/rear and left/right weight transfer ([G], [E]). When pitching caused by acceleration and braking or rolling during turning vary the load on the tires, the tire gripping force also varies. To determine the amount of

variation under these circumstances, tire side slip angle α estimation is corrected. To take an example: on dry road surfaces (estimated road surface μ close to 1) when there is a greater chance of an effect from weight transfer, the lateral acceleration and yaw rate calculated from estimated tire slip angle for each wheel are respectively compared with values obtained from sensors, enabling correction of estimated α .

- (6) To increase the accuracy of estimated tire slip λ , estimated vehicle speed is constantly corrected using nonlinear tire slip data and values obtained from the longitudinal acceleration sensor ([B], [C]).

4. Vehicle Test Evaluations

5.1. FR Vehicle Test Data (Compact Snow Course)

Figure 7 shows data obtained from tests using an FR vehicle on a winding course and a cornering course with a regular 200 m radius. Both courses were covered with compact snow (actual μ value approximately 0.3). Tests on both courses were conducted with closed loop steering input.

These data demonstrate the basic stability of estimated road surface μ and its proximity to actual μ under both dynamic and static conditions. In addition, the estimated vehicle side slip angle β almost exactly corresponds with the side slip angle measured by the sensor, and the estimated lateral acceleration maintains a high level of accuracy, staying close to the values obtained from the lateral G sensor.

These results indicate that the newly developed μ estimation logic satisfies basic performance requirements. However, no slip control, such as provided by VSA, was in operation during this test. The next section discusses a test of road surface μ estimation while slip control is in operation.

5.2. 4WD Vehicle Test Data (Dry Course, Wet Basalt Low μ Course)

The newly developed estimation logic was tested next using a 4WD vehicle with four-wheel slip control in operation on differing road surfaces and under differing

driving conditions. Representative examples of the data obtained from these tests are shown in Figs. 8, 9 and 10. Figure 8 shows winding driving on a dry course, Fig. 9 shows slalom driving on a low μ wet basalt course, and Fig. 10 shows a μ jump from a dry course to a low μ wet

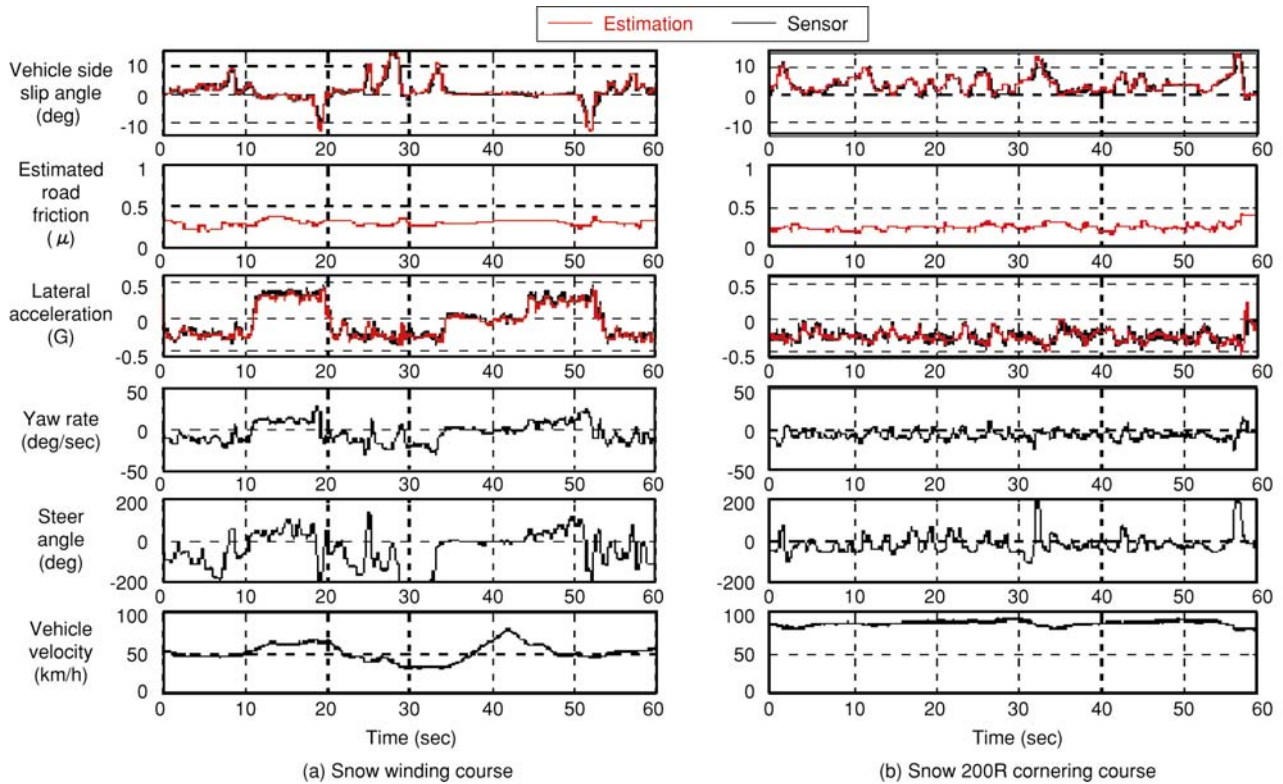


Fig. 7 FR vehicle test data at snow course

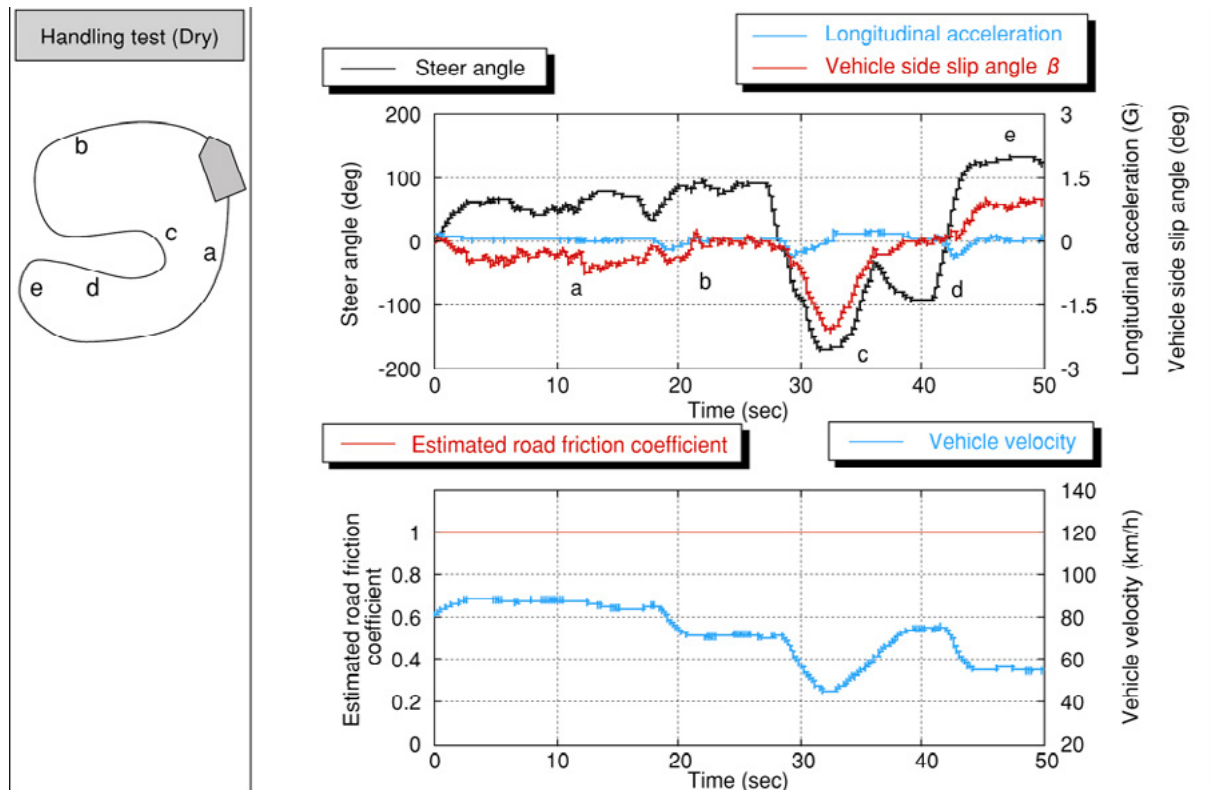


Fig. 8 4WD vehicle test data on dry winding course

basalt course.

As the graphs show, the logic was able to estimate road surface μ more accurately and in real-time, and maintained accuracy under dry, low μ and μ jump conditions. To explain this test data more thoroughly:

(1) Figure 8: Winding driving on dry course

Road surface μ was normalized to 1 for the dry course. As can be seen from the lower graph in Fig. 8, one circuit of the course was sufficient for the logic to determine that

the surface was dry. In addition, estimation of vehicle side slip angle β was stable, and road surface μ estimation functioned more accurately during turning.

(2) Figure 9: Slalom driving on low μ wet basalt course

The lower graph in Fig. 9 shows that estimated μ remained close to measured values even during slalom driving on a surface with a low μ value of approximately 0.3 to 0.4. In addition, when the vehicle demonstrated unstable OS behavior and VSA four-wheel λ control was

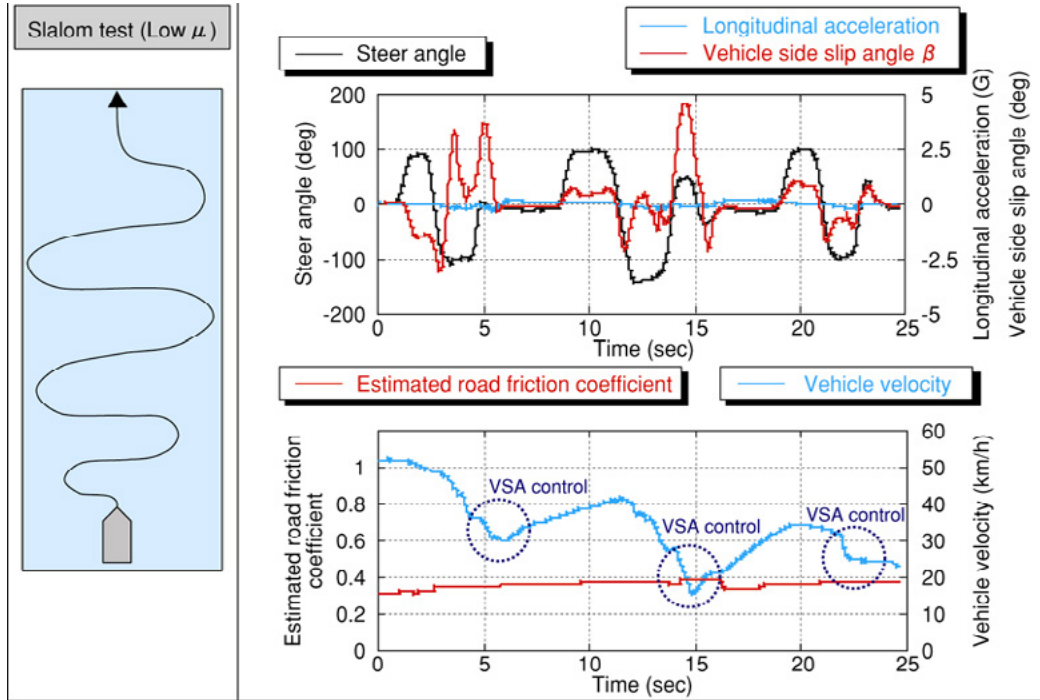


Fig. 9 4WD vehicle test data on low μ slalom course

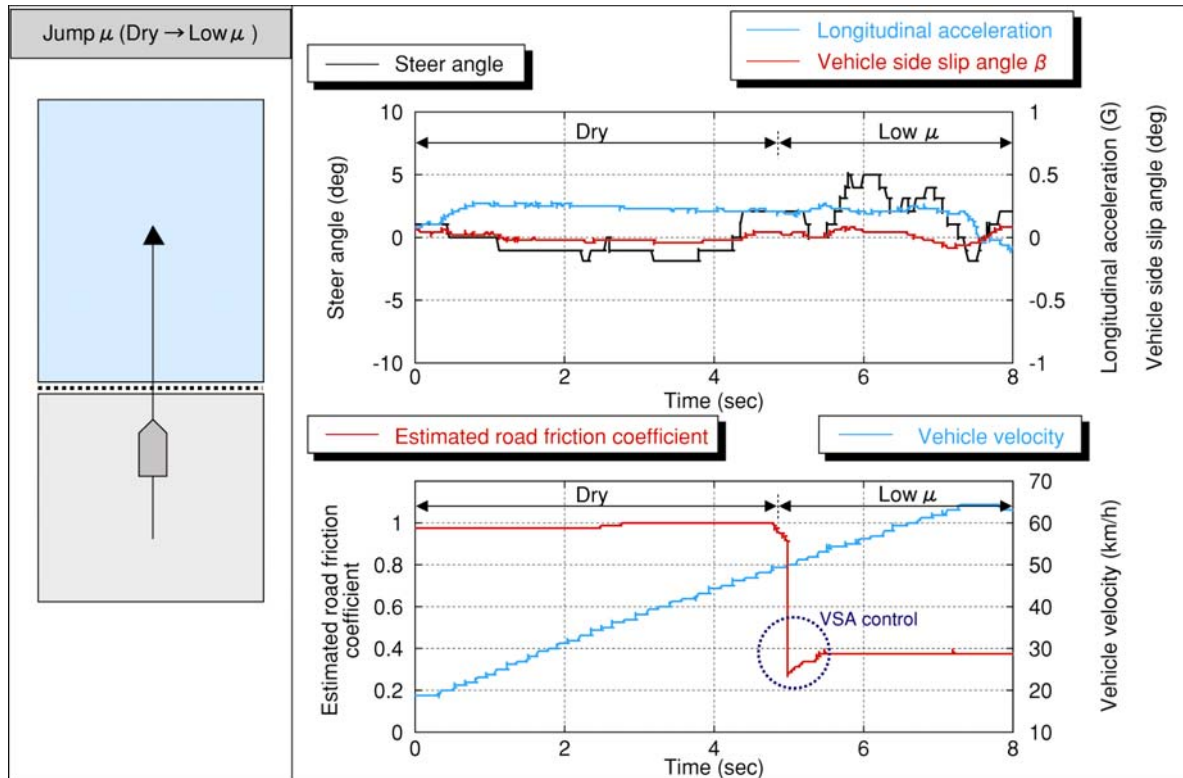


Fig. 10 4WD vehicle test data on jump μ course

in operation, estimation was stable and showed high accuracy. These results show that the new μ estimation logic can be utilized when driving on icy and snowy roads.

(3) **Figure 10:** μ jump from dry surface to low μ wet basalt course

The lower graph in Fig. 10 shows that the μ change occurring when accelerating from a dry surface to a low μ was accurately responded to within a few 100 msec. Besides, μ estimation was stable although λ control was operating to prevent the drive wheels slipping. These results demonstrate the high level of real-time performance of the newly developed logic.

These tests results demonstrate the capability of the new logic to estimate road surface μ more accurately and in real-time for straight, turning and jump μ driving conditions on all road surfaces. Vehicle tests have therefore confirmed the validity of the newly developed μ estimation logic.

6. Conclusion

The following conclusions may be drawn on the basis of the foregoing discussion:

- (1) A μ estimation logic has been developed which is accurate to within ± 0.05 regardless of road surface conditions or driving mode.
- (2) This logic enables stable μ estimation even during the operation of tire slip control in VSA and similar systems.
- (3) The logic estimates μ more accurately and in real-time when μ jump occurs (in particular from high μ to low μ).

These findings show that the targets of this research project have been achieved.

In the future, the authors intend to further develop the range of applicability of this basic logic by creating a technology enabling real-time self-learning correction for fundamental tire characteristics able to function even when tires with different characteristics are fitted.

References

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