Vehicle Velocity and Road Friction Coefficient Estimation for Anti-lock Braking System

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***Abstract*—Many studies take the slip as the major input for anti-lock braking system (ABS) controller. However, slip can only be calculated by vehicle velocity and wheel speed. The vehicle velocity cannot be measured by low cost sensors. In this paper, a vehicle velocity estimation and a friction coefficient estimation methods are proposed. The vehicle velocity estimation just requires wheel speed, wheel deceleration, brake pedal flag, and ABS enable flag. During the estimation, the friction of the road can also be obtained. The methods have been applied to real car ABS test data. There are four different road surface conditions including uniform low friction(μ), high μ, and μ jump from both low to high and the opposite. According to the results, the deviation between estimated velocity and the ground truth is at maximum 1.57 m/s on μ jump road surface which is from high μ to low μ. As for other road surfaces, it provides more accurate outcome. The corresponding estimation of friction coefficient is close to reality. Moreover, the results show that the transition of road condition can be detected quickly. The proposed methods are proved effective for velocity estimation and friction coefficient estimation, which are beneficial for ABS control.**

Keywords—Vehicle Velocity Estimation, Road Friction Coefficient Estimation, Anti-lock Braking System

I. Introduction

Because of the rise of safety awareness and the increase in vehicle electronic applications, the advanced driver assistance system (ADAS) is promptly developed. In ADAS, one of the longitudinal control systems, Anti-lock Braking System (ABS), has drawn huge attention because it relates with vehicle safety and stability. ABS prevents wheels from locking up to avoid vehicle spinning and further increase braking efficiency. ABS can also help drivers maintain steering stability to deal with potentially dangerous conditions. Evans et al. [1] say that ABS can reduce the risk of crash by (32 ± 8)% on low friction surface. It is now a standard system in modern vehicles.

ABS has been developed for many years. Leiber et al.[2] mention that Bosch has been working on ABS development since 1905. Through a long period of development, some ABS methods have also been proposed such as rule-based control, fuzzy logic control, neural networks control, proportional integral derivative control, linear quadratic regulators control, sliding model control, classical robust control, and model predictive control etc. Pretagostini et al.[3] studied many ABS control papers and categorized them. So far, some of the ABS control methods [4]-[6] take the slip as the input for ABS controller. The slip is the ratio of deviation between vehicle velocity and wheel speed, so it is need the vehicle velocity information for calculation of slip and further ABS control logic. S. B. Choi[4], for instance, takes the rear wheel speed as an index to find the corresponding friction, so to find an optimal target slip value as its control target for ABS. In that paper, it is also mentioned that the authors tried to estimate vehicle velocity, but estimations were not accurate enough for the application. G. F. Mauer [5] designed the fuzzy logic controller for ABS. The controller takes four inputs including the road condition identifier, the current and predicted slip ratio, and the braking torque command. It states that all existing ABS braking controllers are limited since there is no practical mean for the direct measurement on slip and friction coefficient. It is not easy to get vehicle velocity for the calculation of wheel slip, because vehicle velocity cannot be measured by low cost sensors, either. Jing et al.[6] states that the wheel slip dynamics is the major focus in the investigation of ABS. It matters with the braking efficiency since the time when the peak μ occurs provides larger brake forces and better brake efficiency. The friction coefficient is proportionally related with the slip in the linear zone and is shown as fig. 1. It will finally reach the maximum value and then decreases. Once the break point is found, it can be selected as the moment to apply ABS. And the slip use the vehicle velocity to calculate. the wheel slip and the vehicle velocity are parameters for the ABS controller. The paper also emphasizes on the accuracy of velocity estimation. Although the estimator is not included in the content, it considers an uncertainty element in the algorithm for the robustness analysis the estimated vehicle velocity.

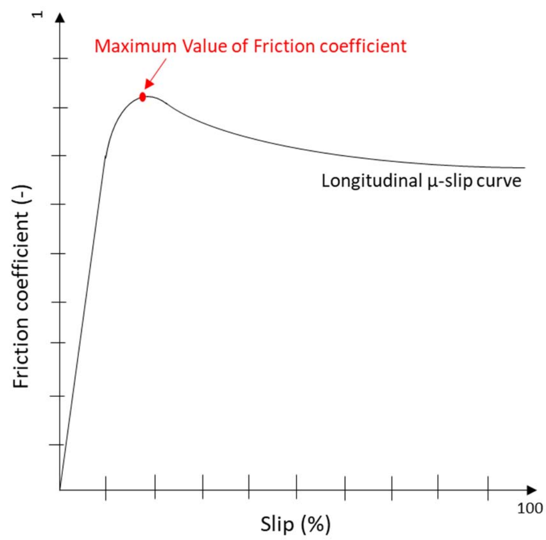

Fig. 1. Relationship between Slip and Longitudinal Friction Coefficient

As what is previously mentioned, the slip and the vehicle velocity are critical to ABS control logics, but none of the papers has clarified the estimating method of vehicle velocity. Therefore, some estimating methods for vehicle velocity have been developed. Song et al.[7] proposed three methods to estimate the vehicle velocity. One of them applies the weighted average algorithm with Kalman Filter. It puts weights on the value of effective tire radius and the tire slip to adjust the estimated wheel speed. The wheel speed can be used to further estimate the vehicle velocity. However, this method highly relies on the accelerometer measurement. It is reasonable to infer that when the ABS is actuated on downhill road conditions, the estimated vehicle velocity may be influenced by the accelerometer bias. Jiang et al.[8] announces an approach which estimates vehicle velocity during ABS operation. When the driver applies the brake, the initial wheel speed is selected as the starting point through the entire calculation. The later-come maximum value of wheel speed will then be selected for the estimation. It occurs after the brake pressure is released and the wheel no longer accelerates. However, as in μ jump surface, the system will not be able to update the change of the road surface since the initial condition is still interpreted instead of the actual μ jump condition.

In this paper, the new method of estimation, which includes vehicle velocity estimation and the friction coefficient estimation, has been proposed. The method requires signals such as wheel speed sensor, ABS module, and brake pedal information to provide the wheel speed, ABS enable flag and brake pedal flag for calculation. Others used for the estimate are calculated by wheel speed, such as the wheel deceleration.

Section II establishes the algorithm architecture and estimation design. In this method, a simple equation for estimation is applied and a dynamic update mechanism is built to update the estimation result by time with respect to the change of wheel speed. This method can be further applied to calculate the road friction coefficient, which may affect the selection of ABS logic and pressure control of the braking valves. Section III demonstrates the experiment details and result analysis which shows the efficacy of the proposed method. In section III, we plan four different road surfaces, including uniform low friction(μ), high μ, and μ jump from both low to high and the opposite as scenarios.

II. System Architecture and Algorithm Design

A. Vehicle Velocity Estimation

Vehicle velocity cannot be obtained from low cost sensors in ADAS, such as ABS. Thus, the vehicle velocity should be estimated. When ABS does not activate, which means there is no slip, the wheel speed will be close to the actual vehicle velocity. It is under the condition when simple acceleration or deceleration is applied. That means, the wheel speed can be taken as the vehicle velocity directly. What brings difficulties for estimation is at the time when the wheel speed change drastically, just as when ABS activates. The wheel speed will no longer be representative to the value of vehicle velocity. To work on it, a method is designed to estimate the vehicle velocity.

This method requires two local maximum value of wheel speed for vehicle velocity estimation. The Concept of the proposed method is shown as Fig. 2. Initially, it takes the wheel speed as the estimated vehicle velocity in the zone before phase 1. There is no slip during simple acceleration and deceleration.

In phase 1, the aim is to determine the very first of wheel speed as the initial value for estimation. Importantly, it is selected as the first local maximum value. However, the next local maximum value may not occur in this phase, so it does not have enough the information about two of the required value for calculation. Thus, a look-up table will be the reference to find the corresponding friction coefficient as the vehicle deceleration for vehicle velocity estimation.

In phase 2, after ABS is active, it chooses two local maximum value of wheel speed to calculate the vehicle deceleration for estimation. It repeats the operation to obtain the estimated value and update the results until ABS shuts down. This method is highly dependent on the selection of local maximum wheel speed. If the local maximum value of wheel speed is close to the real vehicle velocity, it is assured to be accurate.

In phase 1 and phase 2, The estimation of vehicle velocity needs to be corrected. The logic is to determine whether the estimated speed is higher than the current wheel speed. If positive, the estimation value will be selected; If opposite, the estimated value will be replaced by the wheel speed. Normally, the vehicle velocity is larger than the wheel speed, even when it is under ABS operation period.

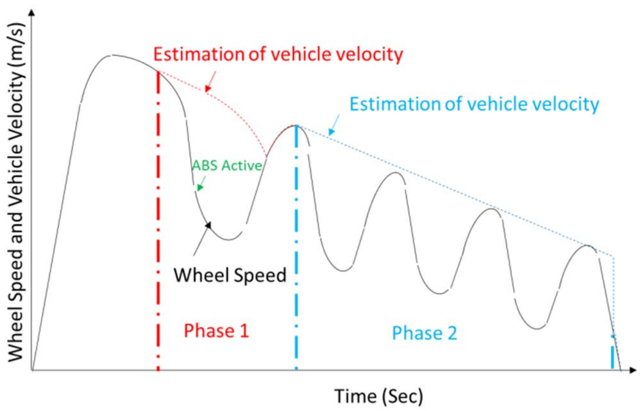

Fig. 2. The Concept of The Proposed Method of Velocity Estimation

During the brake apply, the estimated vehicle velocity can be calculated according to Newton's second law as shown in eq. (1). How well the equation works is based on the accuracy of the selected v_k and a_k.

$$v_{est,k} = v_k + a_k t \quad (1)$$

where $v_{est,k}$ is the estimated vehicle velocity, v_k is the initial value for each estimation, a_k is the vehicle deceleration in m/s^2, t is the sample time. For instance, as the brake pedal is pressed and the wheel deceleration exceeds 5 m/s^2, the corresponding wheel speed is extracted as the initial value. After the first estimation, the initial value will further be updated by time with the previously estimated vehicle velocity for the next estimation. The equation is as shown in eq. (2).

$$v_k = v_{est,k-1} \tag{2}$$

In this approach, we only need a wheel speed sensor to provide wheel speed to calculate vehicle velocity without accelerometer. The accuracy of the vehicle deceleration is important for the proposed method, especially when the wheel speed changes rapidly as ABS activates. It will cause a gap between the wheel deceleration and vehicle deceleration and the slip will grow up at same time.

The proposed method chooses the two local maximum value of wheel speed in the neighborhood. It is for calculating the wheel deceleration as well as the vehicle deceleration. The vehicle deceleration as shown in eq. (3).

$$a_k = \frac{\Delta v_w}{\Delta t} \tag{3}$$

where Δv_w is the deviation between two selected local maximum value of wheel speed, Δt represents the time between two local maximum value of wheel speed. The vehicle deceleration will further be updated if the new local maximum values of wheel speed are found.

The estimated velocity will further be updated by time according to the change of initial value and local maximum value of wheel speed. The flowchart of velocity estimation is shown as Fig. 3. The estimation is based on ABS status. Four main discriminants are adopted in this method. They are described as following steps :

- The initial value of velocity is selected when the driver hits the brake pedal and the wheel reaches threshold.
- The ABS state should be obtained as a flag to search the local maximum value of wheel speed for velocity estimation.
- The local maximum wheel speed should be extracted as a reference to update the data of vehicle deceleration. If it is not obtained, the vehicle deceleration calculation will be based on μ, which is from a look-up table with the wheel deceleration as the input. Here, the μ is used as the vehicle deceleration for further estimation.
- As the estimation is completed, the estimated velocity will be judged whether it is lower than wheel speed. If positive, the estimated velocity is chosen as the output; if not, the current wheel speed will be set as the output.

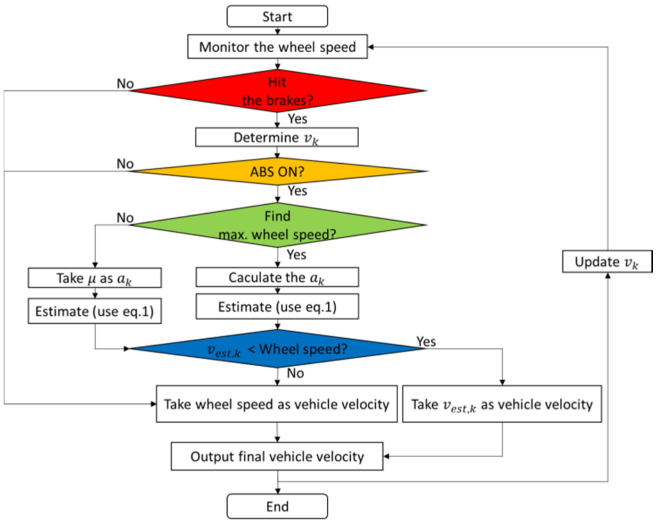

Fig. 3. Flowchart of Velocity Estimation

B. *Road Friction Coefficient Eestimation*

Besides velocity estimation which is mentioned in the previous section, the friction coefficient of the road surface can also be obtained during the procedure. since the wheel slip is related to the road friction. However, this method is different from the previous section(the look-up table).

The condition can be seen in Fig. 1-2. As ABS operates, it will decrease brake pressure to keep the wheel from lockup until the slip is lower than threshold If opposite, it will increase brake pressure and the slip will increase as well. It shows how ABS makes the wheel slip float. No matter how ABS works, there will always be a minimum value of wheel slip. The estimation of friction coefficient as shown in eq. (4).

$$\mu = a_k/(1 - s_{ABS}) \tag{4}$$

Where s_{ABS} stands for the value of minimum slip when ABS operates.

C. *Eestimation Architecture*

The vehicle velocity and road adhesion estimation method are combined as a system which is shown as fig. 4.

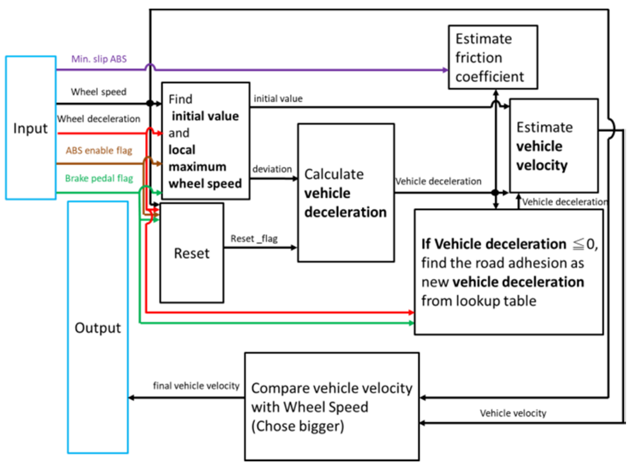

Fig. 4. Block Diagram of System Architecture

III. Experiment and Results Analysis

A. Experiment Settings

In this paper, a commercial vehicle was chosen for ABS testing, and the related vehicle dynamics are recorded for post-processing. The test driver applied the brake at 13.9 m/s and then the ABS was activated. In reality, the road adhesion may not be uniform. However, for simplicity, this paper takes some road adhesion such as uniform low friction(μ), high μ, and μ jump from both low to high and the opposite in the test.Estimation of Velocity on Uniform Road Surface

B. Estimation of Velocity on Uniform Road Surface

The wheel speed of test vehicle was used as the input of the proposed method. The velocity can be estimated through the whole process of braking. How accurate the velocity is estimated is critical for ABS. The comparison of estimated velocities and ground truth, velocity deviation, and friction coefficient are shown in Fig. 4 and 5. The velocity deviation shows that the maximum gap on the high friction road reaches 1.11 m/s at 21.03s. It can also be seen that the estimated friction coefficient is close to the physical friction limit of the surface.

For uniform low μ surfaces, it provides a more accurate estimation. The velocity deviation shows that the maximum gap is 0.6 m/s at 31.23s. The estimated friction coefficient is close to the actual value too. Although there is an impulse at 34.5s, the value is updated quickly to be close to actual condition. One thing worth mentioning is that ABS deactivates in low speed, the period below 2.78m/s is not taken into account for further calculation.

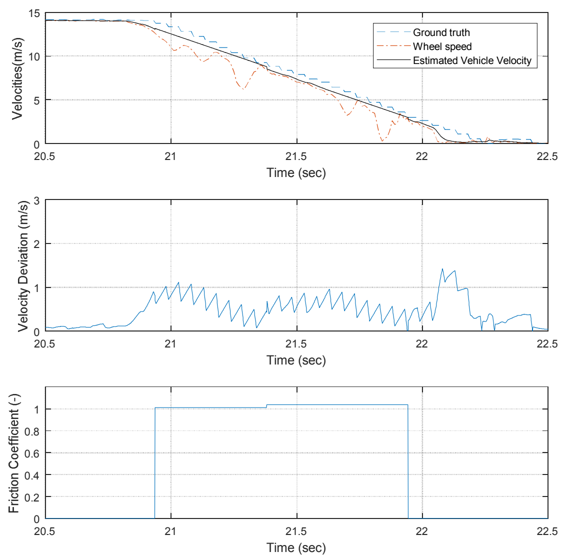

Fig. 5. Estimate the Velocity and Friction Coefficient on High μ Road Surface

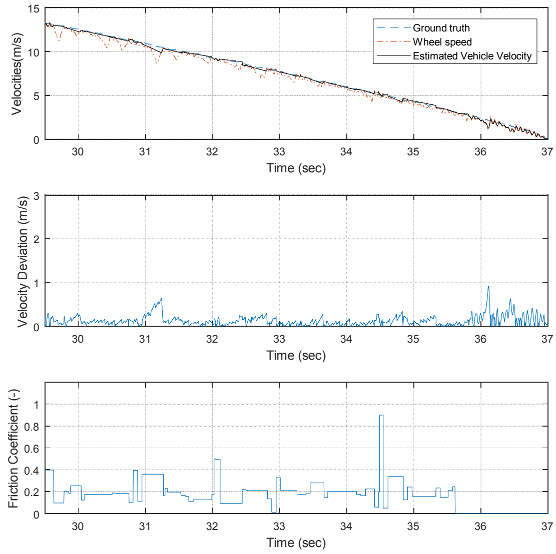

Fig. 6. Velocity and Friction Coefficient estimation on Low μ Road Surface

C. Estimation of Velocity on μ Jump Road Surface

In μ jump condition, the main target is to assure that the estimator is capable of providing accurate estimated velocity and friction coefficient. The key point is to assure whether it can detect road changes quickly enough. Later comes the statement of result analysis.

The results of velocity and friction coefficient estimation is shown as Fig. 6 and 7. Initially, the gap between the estimated and the actual value is large, but it converges and gets close to the ground truth soon. The velocity deviation reaches 1.27 m/s from low μ to high μ, For the opposite scenario which is from high μ to low μ, the velocity deviation reaches 1.57 m/s. The deviation in both scenarios decrease dramatically and are kept stable till the end. because the estimator can detect the deceleration quickly. It is the reason why the estimated velocity is close to reality even when driving on μ jump surface. The estimation can be quickly updated. The effect can also be seen in friction coefficient estimation. It proves that the method can be adaptive to the change of road surface. It can make ABS able to instantly control the related actuator as slip gets larger than the threshold. The stability of the vehicle is thus assured. ABS was deactivated below 2.78m/s.The wheel speed is not taken into account for further calculation.

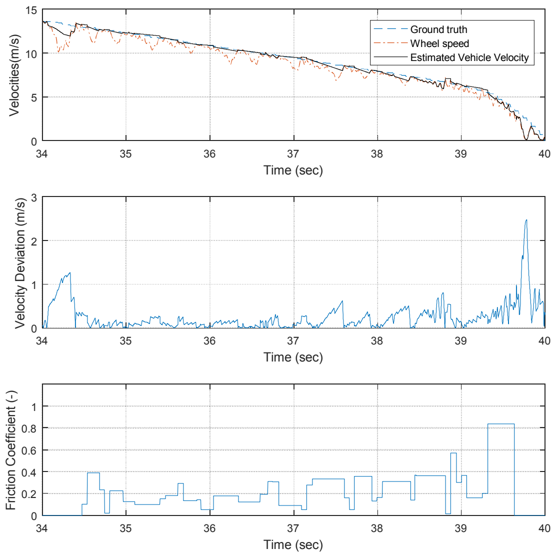

Fig. 7. Velocity and Friction Coefficient Estimation on μ jump Road Surface, from Low μ to High μ

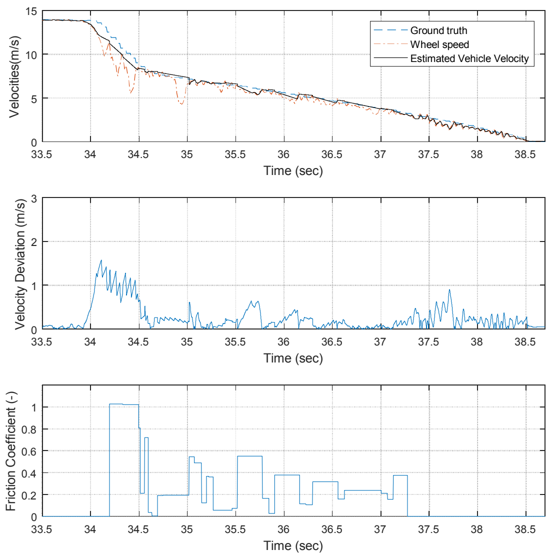

Fig. 8. Velocity and Friction Coefficient Estimation on μ Jump Road Surface, from High μ to Low μ

IV. Conclusion

The vehicle control system is designed more and more intelligent, making assistance system more comprehensively functional. However, in ADAS, not all the input signals can be obtained through production sensors. The reason is mainly due to the cost. Accurate estimators thus stands as an important role. In this paper, a method for estimating vehicle velocity and friction coefficient for ABS is built and tested throughreal vehicle test data. According to the analysis of results, it can be seen that the estimator is capable of providing accurate vehicle velocity, which is critical to longitudinal control. The velocity deviation is at maximum 1.5 m/s on the u jump surface. It also shows that the estimator can be adaptive to different road surface. It is even available in the u jump road condition.

Moreover, it can be seen from the result that the friction coefficient estimation is close to reality. Although there are small amount of section with large deviations during the tests, they are too temporary to reduce the performance of ABS operation.

Accurate estimation of friction coefficient makes the optimization of ABS control possible. For example, after obtaining the friction coefficient, the road conditions can be distinguished and the system parameters can be adjusted adaptively. The performance of the ABS can be improved.

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