

# An Adaptive Nonlinear Filter Approach to Vehicle Velocity Estimation for ABS

Fangjun Jiang, Zhiqiang Gao  
Applied Control Research Lab.  
Cleveland State University

## Abstract

A novel approach to vehicle velocity estimation is proposed. To be cost effective, the estimation is based solely on wheel speed measurement without any additional information on vehicle acceleration. This is made possible by employing an adaptive nonlinear filter scheme which proves to be simple and efficient. Simulation results from field-testing data show that this method results in accurate and smooth vehicle velocity estimation and it is practically feasible.

Keywords: ABS, Vehicle Velocity Estimation, Nonlinear Filter.

## 1. Introduction

The objective of an Antilock Brake System (ABS) is to prevent wheels from lockup. Wheel lockup often happens when braking on a wet and slippery road or during a severe braking. During wheel lockup, vehicle loses steering control and the friction force, which stops the vehicle, is greatly reduced.

In normal drive condition, vehicle velocity is almost same as wheel velocity. Conventional speedometer calculates and displays the speed of a vehicle by measuring the speed of wheel rotation and multiplying it with the nominal wheel radius. However, when a wheel becomes lockup and slips, vehicle velocity and wheel velocity can be quite different. In ABS control, we use "slip" to indicate the difference between wheel velocity and vehicle velocity. Slip is defined as:

$$slip = \frac{V - \omega R}{V} \quad (1.1)$$

where  $V$  is the vehicle velocity,  $\omega$  is the wheel angular velocity and  $R$  is the rolling radius (wheel and tire). Without braking,  $V \approx \omega R$  and therefore  $slip \approx 0$ . In severe braking, it is common to have  $\omega = 0$  while  $V \neq 0$ , or  $slip = 1$ , which is called wheel lockup.

Now, let's review the relation between slip and friction. It is well known that the friction force between tire and terrain is a nonlinear function of

slip. Figure 1 (From [1]) illustrates the friction coefficient,  $\mu$ , and slip curve. It shows that the maximum friction is obtained when slip is close to 0.2. Note that this  $\mu$ -slip curve changes for different road surfaces and vehicle speeds and the optimum slip value also varies.

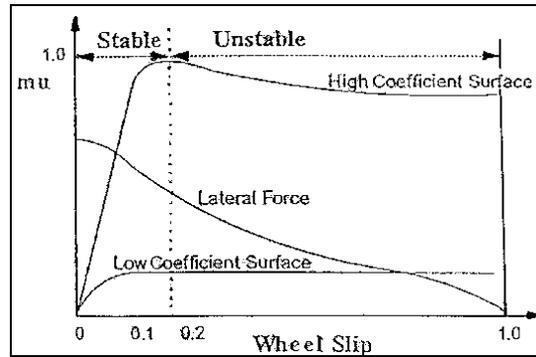


Figure 1: Coefficient of friction vs. wheel slip

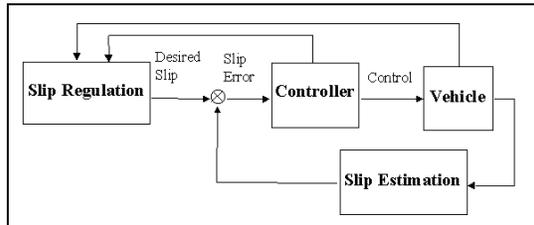
The lateral force shown in Figure 1 is essential to the steering of vehicle. It is obvious when slip = 1, this force is zero, which explains why the steering ability is lost during wheel lockup.

ABS is designed to manipulate wheel slip so that a maximum friction force is obtained and the lateral stability is maintained. Since its appearance on the market in 1960s, ABS has become more and more popular and is now available on almost all types of vehicles. It is regarded as another major contribution to road safety after airbag.

ABS is usually implemented in an ECU (Electronic Control Unit, which is a micro-processor based control system). In a severe braking situation, ECU assists the operator to prevent wheel lockup by regulating wheel slip. It monitors wheel velocity and vehicle velocity. When lockup is detected or deemed eminent, ECU releases brake pressure to allow wheel velocity to increase and wheel slip to decrease. Once the wheel velocity spins up, ECU re-applies brake pressure to confine wheel slip to a predetermined value or interval.

## 2. Problem of Vehicle Velocity Estimation

Various types of control algorithms have been implemented in commercial ABS products or discussed in publications [2], [3], [4], such as state machine method, fuzzy logical control and slip control. Regardless of the differences in these ABS algorithms, one of the common and most important issues in ABS control is the measurement or estimation of the vehicle velocity over ground.



**Figure 2:** Basic ABS control structure

Figure 2 shows a basic structure for ABS control. Accurate slip calculation is a key of ABS control. From (1.1), it is clear that no matter what algorithm is applied, true vehicle velocity is always the basis for slip calculation. Wheel angular velocity can be measured easily and accurately by using wheel angular sensor. However, direct measurement of vehicle velocity such as optical correlation method or spatial filtering method, although available, is often too expensive and requires additional wiring, which makes the system more complex. Relying on an additional sensor also makes the system more prone to sensor failures, thus lowering overall system reliability.

#### Literature Review:

An alternative is to estimate the vehicle velocity from the existing information, particularly the wheel velocity measurements. Many efforts have been focused on the issue of vehicle velocity estimation [4], [5], [6], [7]. In [4], Bowman and Law extensively discussed the issues of ABS. They gave two suggestions to the solution of vehicle velocity measurement. The first option is direct measurement and calculation, which needs either four accelerometers installed at each wheel hub or two accelerometers installed at the center of gravity of the car, a yaw rate gyroscope and a steering wheel angle sensor. The second option is an estimation method using state estimator discussed in [7].

Kalman filter and fuzzy logic estimation were investigated in [5] and [6]. In [5], wheel velocity and vehicle acceleration signals are available, the vehicle velocity is estimated using Kalman filter based on a “signal model”, which assumes the

derivative of vehicle acceleration is a random “noise” input. Fuzzy logic is used to adjust the parameters for Kalman filter. Experiments conducted on an actual vehicle show that accurate estimation of the absolute vehicle velocity is achieved even under significant braking skid and traction slip conditions. In [6], wheel velocity, vehicle acceleration as well as vehicle yaw rate signals are available. No dynamic model or even simplified model for vehicle is needed. The fuzzy logic estimator derived the vehicle velocity as a weighted sum of the measured wheel velocity plus the integrated and corrected acceleration. Off-line calculation shows that equal quality of estimation is achieved comparing with conventional Kalman filter. In [7], the method of extended Kalman filter is applied to estimate the vehicle velocity and tire force. The vehicle and tire model is a nine degree-of-freedom nonlinear model and a five degree-of-freedom vehicle model is used in the estimator. Simulation shows that real-time filtering can be achieved to provide state estimates for feedback control.

All these methods reviewed above as well as other publications require at least one more sensor except the wheel velocity sensors (for example, sensor for vehicle longitudinal acceleration).

#### Motivation for Further Research:

In our effort, we focus on a class of ABS problems where the vehicle velocity is to be estimated from only two or four measured wheel velocities. There are no acceleration or yaw rate signals available. Such problems are common in heavy vehicle ABS and are usually dealt with by using a trial and error approach. It usually results in a long program based on human heuristic. It tends to be hard to tune and update.

Our objective in this research effort is to develop an analytical and practical solution to this problem. In particular, an adaptive nonlinear filter approach is proposed to estimate the vehicle velocity based on the wheel velocities. The resulting computer program is short, easy to understand and tune. It is tested on the data collected from field-testing of real heavy vehicles. The results demonstrate that this approach is efficient and practically feasible.

### **3. Main Results**

The unique problem of obtaining vehicle velocity from the wheel velocity measurement is quite challenging. In general, when vehicle is in normal drive, the vehicle velocity is fairly close to

the wheel velocity and the problem can be viewed as a filter design issue, where the input to the filter is wheel velocity and the output is vehicle velocity. However, during the wheel lockup or near lockup situation, this relationship no longer holds. This is where other information, such as the road surface condition and in what phase the ABS is operating, is needed to help to estimate the vehicle velocity.

**The Nonlinear Filter:**

The mathematical equation of the nonlinear filter is:

$$\begin{aligned} \dot{y}(t) &= -R \cdot \text{sign}(y(t) - x(t)) \\ y(t=0) &= y_0 \end{aligned} \quad (3.1)$$

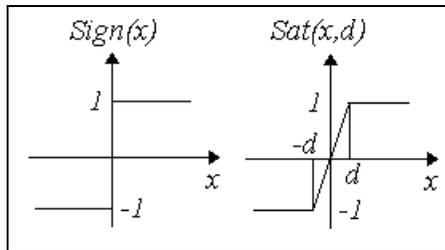
where  $x(t)$  is the input and  $y(t)$  is the output.  $R$  is a constant and  $y_0$  is the initial value of the output.  $\text{Sign}(\ast)$  is the sign function, which is defined as:

$$f(x) = \text{Sign}(x) = \begin{cases} 1, & \text{when } x > 0 \\ 0, & \text{when } x = 0 \\ -1, & \text{when } x < 0 \end{cases} \quad (3.2)$$

In real implementation, a saturation function  $\text{Sat}(x)$  is used in replace of  $\text{Sign}(x)$  to prevent numeric oscillation. The saturation function  $\text{Sat}(x)$  is defined as:

$$f(x) = \text{Sat}(x, d) = \begin{cases} 1, & \text{when } x > d \\ -1, & \text{when } x < -d \\ x/d, & \text{else} \end{cases} \quad (3.3)$$

where  $d$  is a small number like  $0.1$ . Figure 3 illustrates the function of  $\text{Sign}(x)$  and  $\text{Sat}(x, d)$ .



**Figure 3:**  $\text{Sign}(x)$  and  $\text{Sat}(x, d)$

The intuition behind this nonlinear filter is that it acts like a bang-bang controller where the output  $y(t)$  will converge to the input  $x(t)$  in steady state. The rate of change in  $y(t)$  is limited by the only gain in this filter,  $R$ .

When  $y(t)$  represents vehicle velocity, the rate of change in  $y(t)$  reflects the condition of the road surface. Therefore, as it is shown below in implementation, the value of  $R$  will be continuously updated to reflect the road condition, thus making the filter in (3.1) an adaptive filter.

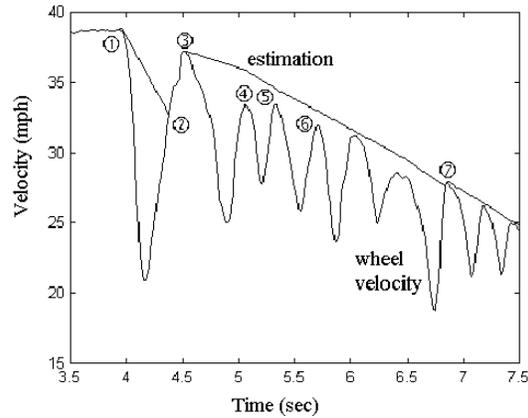
**The Operation of the Adaptive Nonlinear Filter:**

For vehicle velocity estimation, the input to the filter in (3.1) is the wheel velocity and the output is the vehicle velocity. An initial value of the gain  $R$  is selected to reflect the maximum deceleration. The filter is continuously updated in the following manner:

1.  $R$  is adjusted to the deceleration rate of the vehicle, which can be estimated at the peaks of the wheel velocity. It is assumed that, at these peaks, the wheel velocity is close to the vehicle velocity;
2. If the wheel velocity measurement exceeds the estimated vehicle velocity, the vehicle velocity is set to be the wheel velocity. This is because a wheel can not spin faster than the vehicle velocity during the braking operation.

**Graphical Illustration:**

The implementation of the algorithm can be illustrated using Figure 4, where the curve with oscillation indicates one of the measured wheel velocities and the other curve indicates the estimation of the corresponding vehicle velocity.



**Figure 4:** Vehicle velocity estimation

Point ① is the starting point of braking where the vehicle velocity is set to be equal to the wheel velocity. At point ①, the wheel velocity starts to decrease dramatically. ECU detects that the wheel deceleration has exceeded certain threshold and then activates the ABS. Obviously, it's impossible for the vehicle to decelerate at such rate. The vehicle velocity is to decelerate at the maximal rate (curve between ① and ②). This maximal rate is set as the initial value of  $R$  (for example, 15 mile per hour per second or  $0.68g$ ). Currently, the maximal deceleration is determined based on a dry, high  $\mu$  road surface. Of course, this can be combined with

a surface identification mechanism to yield more accurate initial value.

At point ②, the wheel velocity spins up and exceeds the estimated vehicle velocity. This indicates the initial rate limit is too large. The estimated vehicle velocity will then follow the wheel velocity until point ③.

At point ③, the wheel velocity reaches its first peak. This peak is usually close to the true vehicle velocity. This value will be assigned to the estimated vehicle velocity and set as the new base of estimation. Also, the slope between ① and ③ provides the information about the vehicle's deceleration during this phase. This is a reflection of the road surface condition. The gain,  $R$ , of the nonlinear filter is adjusted at this point.

Every time the wheel velocity reaches its peaks, such as points ④, ⑤, and ⑥, the  $R$  is modified to reflect the current vehicle deceleration rate. At some points, like point ⑦, the wheel velocity exceeds the estimated vehicle velocity. This means the former estimation is a little low and the rate limit is a little high. At this point, the wheel velocity will be set as the new estimated vehicle velocity and the rate limit will be modified again using the value of this peak.

To make the estimation less sensitive to noisy peaks, the deceleration rate limit is defined as the slope between the peak and the start point of ABS (point ①), rather than the slope between two adjacent peaks. To accommodate potential changes in road surface condition and the overall nonlinearly curve of vehicle deceleration, the rate limit  $R$  is set to be increasing at a fixed rate, but never exceeds the maximal deceleration.

For vehicles with four wheel sensors, there will be four estimates from four measured wheel velocities. The final estimated vehicle velocity is set to be the maximal estimate during braking and the minimal estimate during acceleration or normal driving.

#### Off-line Tests:

We tested this algorithm off-line using real field-testing data provided by Truck Brake Systems Co., AlliedSignal Inc. On the testing vehicle, a bicycle wheel, known as the fifth wheel, is installed to measure the real vehicle velocity. Velocities are sampled every 15 ms. The results from various configuration and road surfaces show that a smooth and accurate estimation is achieved (see Figure 5 to Figure 7).

#### **4. Summary and Conclusion**

The accurate measurement or estimation of

true vehicle velocity still remains a problem in automotive industry. In our configuration, this problem becomes more challenging since only wheel velocity is measured. No vehicle acceleration signal is available. We developed this adaptive nonlinear filter method based on the characteristic of wheel velocities and our knowledge of ABS operation. An assumption is made, based on available data and the way ABS operates, that the wheel velocities periodically reflect the real vehicle velocity. The off-line test results show that it gives an accurate and smooth estimation.

Since the road condition and vehicle's deceleration rate are unknown to begin with, the estimation error seems inevitable when ABS is first applied. But, it is demonstrated in the test results that the proposed algorithm is able to recover from this initial error and converge to the true vehicle velocity.

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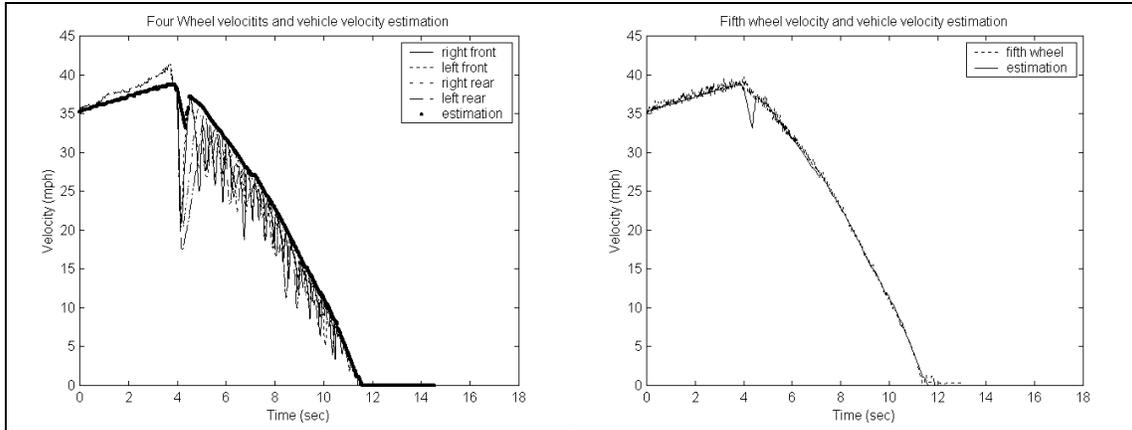
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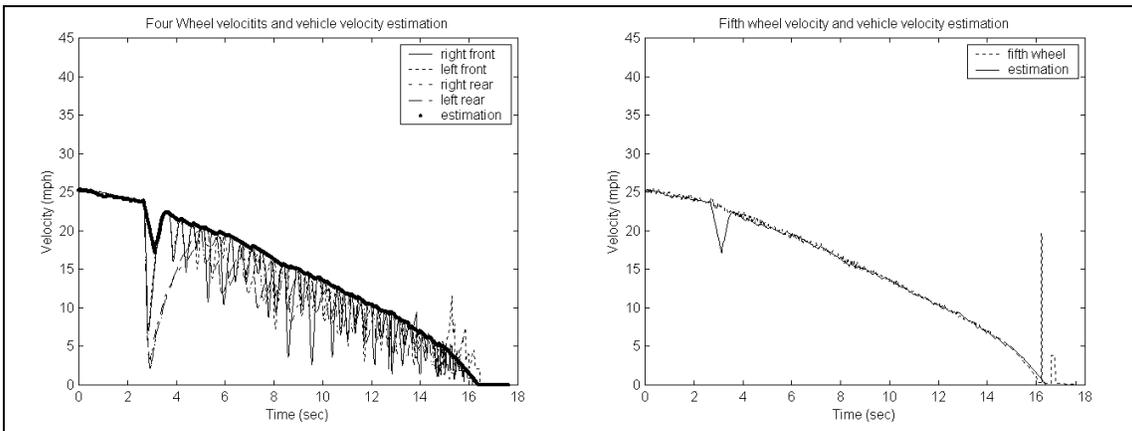
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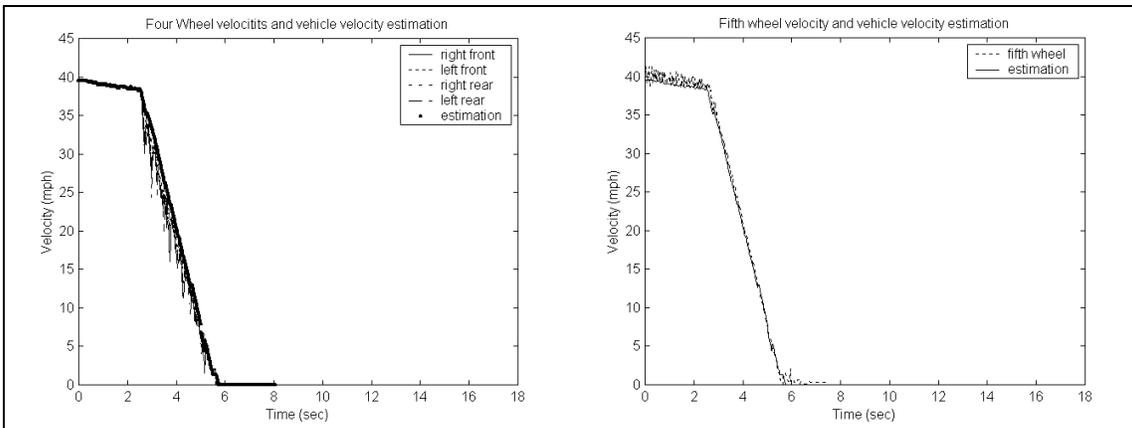


**Figure 5:** Test # na100, low coefficient surface (wet epoxy)



**Figure 6:** Test # trcc058, 500 radius turn and braking on moderate slippery surface

(Left front wheel is ignored due to the obvious noise. The noise in fifth wheel velocity at the end of testing will not affect the comparison.)



**Figure 7:** Test # sbn075, high coefficient surface (dry asphalt)