# An Experimental Laboratory Bench Setup to Study Electric Vehicle Antilock Braking / Traction Systems and their Control

P.Khatun C.M.Bingham N.Schofield
Electrical Machines & Drives Group,. Dept. of EEE
University of Sheffield
Sheffield, S1 3JD, UK

P.H.Mellor
Industrial Electronics Group, Dept. of EEE
University of Bristol
Bristol, BS8 1UB, UK

**Abstract— This paper describes the preliminary research and implementation of an experimental test bench set up for an electric vehicle Antilock Braking System (ABS)/Traction Control System (TCS) representing the dry, wet and icy road surfaces. A Fuzzy logic based controller to control the wheel slip for electric vehicle antilock braking system is presented. The test facility comprised of an induction machine load operating in the generating region. The test facility was used to simulate a variety of tire/road $\propto$-$\sigma$ driving conditions, eliminating the initial requirement for skid-pan trials when developing algorithms. Simulation studies and results are provided.**

***Keywords*****—Fuzzy logic control, ABS, traction control, braking, electric vehicle.**

## I. INTRODUCTION

Increasingly stringent regulations for emissions from automotive vehicles has led to a resurgence of research activity to realize alternative electrically driven power-trains with comparable performance attributes to their internal combustion engine counterparts. The development of vehicles with electrically actuated wheels has made it possible to develop anti-lock braking/traction control (ABS/TC) strategies, due to the inherent localized control of wheel torque.

The objective of ABS controller is to control the wheel slip at some optimum value. ABS/ traction control dynamics tend to be non-linear, time varying and complicated, thus resulting in a complicated classical control system. The performance of classical ABS/traction control systems is often limited by the mechanical bandwidth of the active actuation systems (typically 20Hz –25 Hz for ABS). In electrically powered vehicles the torque output of the motor is directly proportional to the current **[1]**, hence ABS/ traction control systems can be designed to provide greater frequency bandwidths.

Another major obstacle to the development of a robust ABS/traction control system has always been the real-time estimation of wheel-slip vs. adhesion-coefficient characteristics for different tire types and road surface conditions **[2]**. Recent investigations have applied observer/estimation schemes to obtain real-time estimated data indirectly, and Extended Kalman Filter (EKF) has received increased attention **[3]**. However, published material to-date is primarily derived from simulation studies, with practical implementation and validation of the techniques being rare. Current commercial/passenger vehicles incorporating ABS/traction control systems often employ look-up tables that are based on the results of experimental trials, and have been shown to provide inadequate performance under many driving situations. This technique however, is limited by the fixed range of control parameters, and is often 'de-tuned' to accommodate worst-case scenarios, for example, traction control in icy conditions with old tires. Consequently, a sub-optimal wheel-slip characteristic is imposed for most driving conditions. This constitutes the safest criteria for design purposes, resulting in imposition of conservative limits on the traction available under higher adhesion coefficient ($\propto$) surfaces. Hence, optimal benefits of the traction controller are often not realised in classical control strategies. In this paper a robust and efficient ABS/traction control system using fuzzy logic algorithms is described. Thus circumventing the issues imposed by the limiting control parameters in classical control.

For the purpose of clarity, a background material of the ABS/ traction control system is given in section II. Section III, shows the experimental set-up using the induction machine in generator mode torque-slip characteristics provides a platform for simulating a variety of tire/road *coefficient of friction vs. slip ($\propto$ vs. s)* driving conditions. Section IV, describes fuzzy logic ABS/ traction control algorithms and implementation in the experimental set-up. Finally, section V presents the data analysis obtained from simulation studies and experimental test.

## II. TRACTION CONTROL / ANTILOCK BRAKING SYSTEMS

The tractive force *($F_L$)* between a tire and the road surface (Figure 1) is proportional to the normal load, *($F_z$)*, the constant of proportionality being termed the adhesion coefficient ($\propto$). The adhesion coefficient $\propto$ is the ratio of

---

The principle author is currently a Product Design Engineer with Ford Motor Company. The subject matter of this paper was originally studied as part of her PhD research at the University of Sheffield, UK. E-mail: pkhatun@ford.com.

tire brake force at the tire road interface and the normal load acting on the tire, i.e:

$$\propto = \frac{F_L}{F_Z} \qquad (1)$$

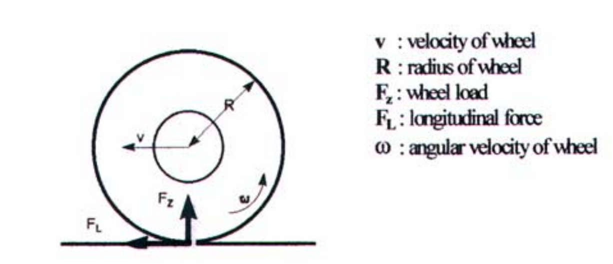

**Figure 1.** Wheel model **[4].**

The value of $\propto$ is highly dependent on tire characteristics (compound, wear, ageing etc) and road surface conditions (dry, icy, gravel, tarmac etc), although it can be primarily regarded as a function of the relative slip, *s*, between the two contacting surfaces. Slip is defined as the normalised difference between the wheel speed and the contact point speed:

$$s = \frac{v - R\omega}{v} \qquad (2)$$

where *v* is the vehicle velocity, *R* is the effective radius of the driven wheel, and $\omega$ is the angular velocity of the wheel. Typical $\propto$-*s* characteristics are shown in Figure 2.

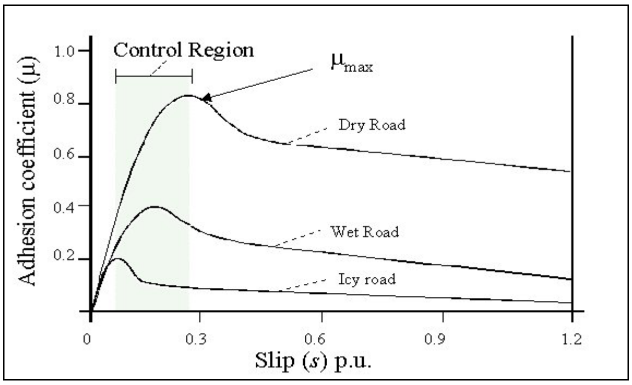

**Figure 2.** Example $\propto$-*s* characteristics for various road conditions **[ 5].**

In the control region, Figure 2 demonstrates that an increase in slip can increase the tractive force between the tire and road surface by virtue of an increase in $\propto$. However, once the peak ($\propto_{max}$) of the characteristic is encountered, any further increase in slip will reduce traction, and consequently induce an unstable acceleration of the wheel until the drive torque is reduced.

The objective of an antilock braking system (ABS) is to manipulate the tractive force applied to the driven wheels in order to limit the slip, *s*, between the road surface and the tire, and consequently only operate within the stable control region of the $\propto$-*slip* characteristic. An obstacle in the design of ABS control schemes is the determination in real-time of $\propto$-*slip* characteristics, i.e. $\propto_{max}$ and slip. Table 1 shows typical values of slip required to obtain the maximum adhesion coefficient, for various road conditions.

| **Road condition** | **Max. adhesion coefficient ($\propto_{max}$)** | **Optimum slip (*s*)** |
|---|---|---|
| Dry Road | 0.85 | 0.35 |
| Wet Road | 0.4 | 0.2 |
| Icy Road | 0.2 | 0.1 |

**Table 1.** Max. values of $\propto$ for various road surfaces **[5].**

Many manufacturers employ a slip-limiting control scheme for ABS/ traction control to account for 'worst-case' conditions, typically the icy road parameters ($\propto$max, slip). Although this constitutes the safest criteria for design purposes, it can impose conservative limits on the traction available under less severe conditions **[6]**. A second issue often encountered by designers of ABS/ traction control schemes, is the inadequacy of appropriate test-tracks/skid-pans or other experimental rolling road facilities (experimental setup) to evaluate proposed algorithms and provide repeatable conditions for comparative studies as described in the following section.

## III. EXPERIMENTAL TEST FACILITY

A low cost experimental test bench was developed. The test facility illustrated in Figure 3, comprises of an electric traction drive, which represents the vehicle drive and is connected to a three-phase induction machine, which is used to imitate the road load, and develop and test control algorithms.

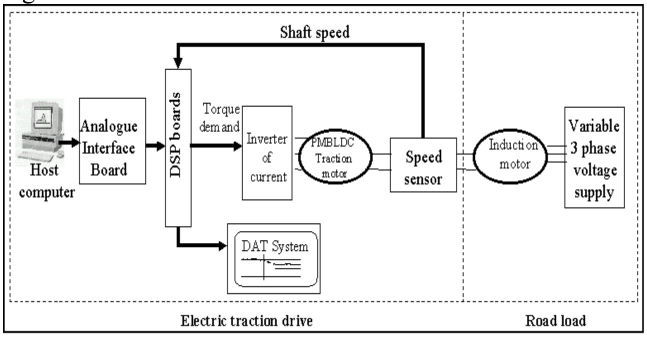

**Figure 3.** DSP based experimental test facilities.

The experimental electric traction drive is a 6kW continuous, 12kW peak rated brushless permanent magnet motor supplied via a power controller from a 72V high performance Nickel Cadmium traction battery. The power electronic controller is constructed using three independent MOSFET / IGBT H-bridge **[7]** and is capable of full four-quadrant operation. In the prototype electric vehicle, the traction motor is connected to the wheels via a step-down gearstage. However, for the test-bench, only steady state operations were carried out. The brushless permanent magnet motor is directly coupled to a 2.2kW, 50Hz, 3-phase, 6-pole, induction machine, the angular velocity of the connecting shaft being monitored via an optical shaft encoder interface. The induction motor is connected to the utility supply via a variac (allowing the supply voltage to be adjusted). To facilitate the implementation of the developed control schemes, a custom state-of-the-art, DSP hardware platform was designed, based on the TMS320C31 floating-point processor, to integrate the system control algorithms with sensor interfaces, man-machine interface's, monitoring, and supervisory tasks. A foreground/background distribution of 'non-time-critical' and 'time-critical' functions has been employed to ensure the controller remains a high integrity process.

The key principle of operation of the test facility for ABS/ traction control is based on the relationship between *∝-slip* characteristics of tire - road interactions( Figure 2), and torque-slip characteristics of the induction machine (Figure 4).The brushless PM motor acts as the prime-mover and drives the induction machine into the generator region of operation, thereby inducing a negative slip with respect to synchronous speed (1000rpm @ 50 Hz in this case). As the torque demand to the PM machine is raised further, the slip becomes increasingly negative, and the induction machine develops an opposing torque, eventually resulting in a stable steady-state condition.

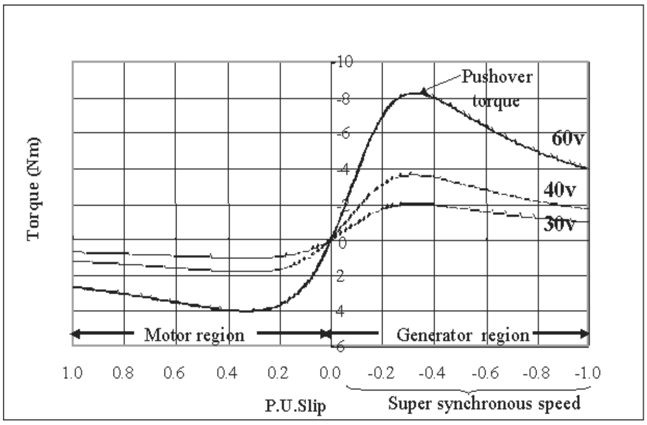

**Figure 4.** Induction machine torque-slip characteristics.

This procedure can continue up to the pushover torque limit of the induction machine. A subsequent increase in applied torque will then further decrease the slip, forcing the system into an unstable operating region. Thus, the induction machine is not able to oppose the applied torque, and a runaway condition is encountered with the brushless motor accelerating uncontrollably. This is analogous to the classical *∝-s* characteristics encountered in traction control systems when the slip at $\propto_{max}$ is exceeded. An algorithm that controls the torque developed by the brushless PM motor to maintain the induction machine in the 'stable-slip' region of operation, is also to be a good candidate to control the torque applied to the wheels to maintain tractive force in the stable region. The steady state torque-slip characteristic is obtained from the equivalent circuit of an induction machine as:

$$\tau_{ind} = \frac{3V^2 R_2 / s}{\omega_{sync}\left(\left(R_1 + R_2 / s\right)^2 + \left(X_1 + X_2\right)^2\right)} \tag{3}$$

where: $V$ is the applied voltage, $R_1$ is the stator resistance, $R_2$ is the rotor resistance referred to the stator, $s$ is the slip, $\omega_{sync}$ is the synchronous speed, $X_1$ is the stator leakage reactance, $X_2$ is the rotor leakage reactance referred to the stator.

The magnitude and shape of the torque-slip characteristics is dependent upon the supply voltage and impedance. By adjusting the voltage and impedance, a wide range of tire/road conditions can be simulated. The induction machine torque-slip characteristic (Figure 4) is calibrated to match the tire slip-adhesion characteristic (Figure 2). During the operation of an induction machine at 0 slip the system is stable and at 100% the system is locked. This is analogous to the braking process of a vehicle, where a wheel can rotate freely with slip at 0 or be locked at slip equal to 1. It is noted that, due to the unsymmetrical nature of induction machine characteristics, different parameters (voltage and frequency) for exciting the induction machine are required to simulate ABS and traction control systems.

## IV. FUZZY LOGIC ABS/ TRACTION CONTROL

To address the braking operation at 0 to 100 % slip, a fuzzy-based technique was employed to develop control algorithms. One of the strengths of fuzzy systems is their ability to express a confidence in reasoning results. Recent studies **[8]** have shown that fuzzy control algorithms are part of a class of universal approximators of continuous functions**.** The advantage of fuzzy control is that there are many instances where TRUE and FALSE or ON and OFF fail to describe a given situation. These cases require a sliding scale where variables can be measured as PARTLY ON or MOSTLY TRUE and PARTLY FALSE.

Traditional set theory is based on bivalent logic where an object is either a member of a set, or not. However, with fuzzy logic, an object can be a member of multiple sets with a different degree of membership in each set. A degree of membership in a set is based on a scale from 0 to 1, 1 being complete membership and 0 being no membership. In fuzzy logic traction control, an output (the torque demand) is calculated based on the amount of membership the input signals (observed load torque and slip) have in the fuzzy sets. Therefore, it is required that the system inputs go through three major transformations before becoming a system output. Figure 5 shows the overall fuzzy logic based traction control scheme. In this figure, the torque demand is compared with the load torque of the induction machine (equation 3), which is analogous to the road surface adhesion coefficient (∝). The induction machine, which is part of the plant model, runs as a generator, driven by a permanent magnet machine (motor). The output of the plant is the wheel speed (induction machine rotor speed calibrated to wheel speed), and the wheel slip (induction machine slip calibrated to the wheel slip). Both of these output parameters are inputs to the discrete time state observer, where the ∝ is calculated. The rate of change of ∝ and rate of change of slip undergo the fuzzy logic control scheme, which includes the transformation process of fuzzification, fuzzy rule reasoning and de-fuzzification.

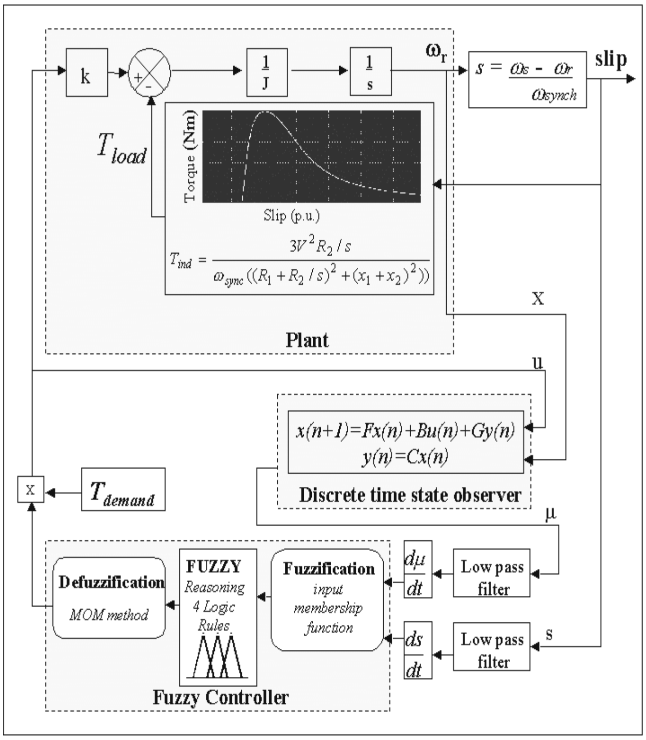

**Figure 5.** Fuzzy Logic based traction control scheme

## V. RESULTS

An example of the simulated performance of the fuzzy control scheme, using an induction generator the slip stabilizes at 0.25 as shown in Figure 6, for a vehicle traveling on a dry road surface ( 60V phase voltage). However in 'bang-bang' slip control where the 'worst case' slip is limited to 0.1p.u. (due to the imposed limit)for dry surfaces **[9]**. It can be seen that the fuzzy scheme automatically adapts the slip control algorithm and identifies the unstable region of the torque-slip curve (-0.35 to -1.0). Eventually the slip stabilized at –0.25 p.u. which is similar to the ∝ *slip* characteristic of a dry road surface (where the peak slip is between 0.25 and 0.35 p.u.).

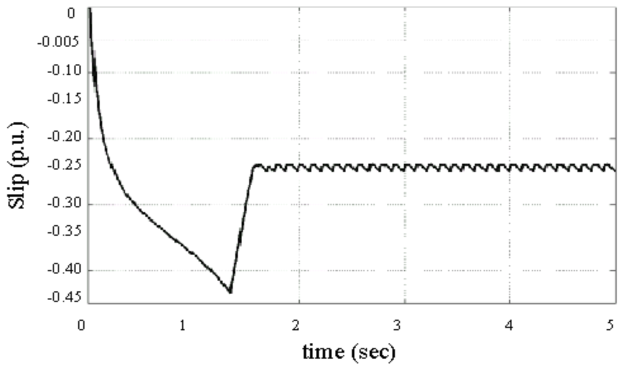

**Figure 6.** Simulation results for road conditions with Fuzzy Logic Control

Let's consider icy road surface, where the fuzzy control system is shown to be unstable. This condition is simulated at lower induction motor phase voltage (35V), and at –0.1 p.u. slip, Figure 7 shows that the system becomes unstable.

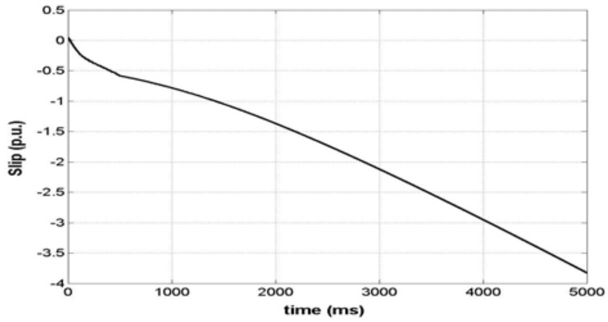

**Figure 7.** Simulation results for road conditions without fine 'tuning' of fuzzy controller.

Fuzzy control with some "tuning" of the input and output membership functions, can provide a more robust system under icy condition. The controller thereby being optimised for lower values of adhesion.

The fuzzy controller was tuned in order to assure optimum control for a vehicle traveling on icy surfaces. As mentioned in section III (Figure 3 and 4) the induction machine was supplied with 33V ac, to represent the icy road surface. Fig 8a, shows experimental drive train shaft torque of 12Nm, was provided by the PM brushless machine. Results shown in Fig 8b demonstrate the fuzzy controller's robustness is sufficient to keep the induction machine from operating in the unstable torque-slip region, especially at low values of adhesion (which is induction machine torque). It was noted that the measured load torque (Fig 8c) was derived from the measured phase current, using the following relationship: *T*∝ *kI*, where the constant *k* is equal to 0.23Nm/A. Finally, Fig 8d illustrates the observed load derived from a discrete time based-observer **[10],** has similar dynamic response as the measured load torque (Figure 8c).

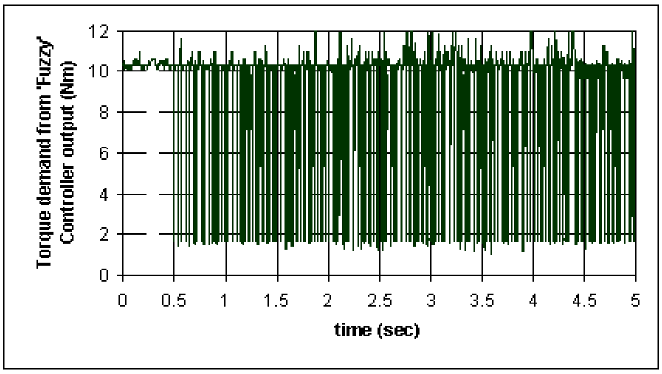

**Fig 8a.** Measured torque demand.

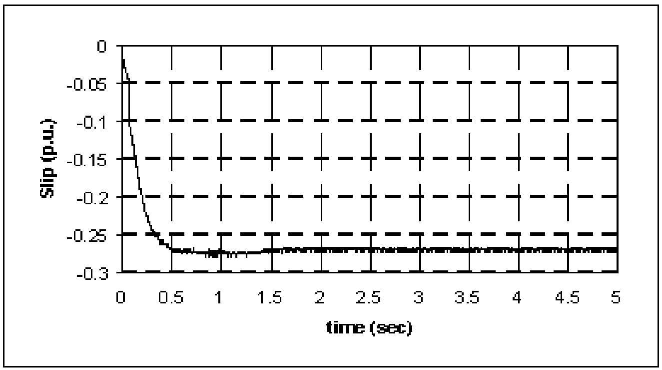

**Fig 8b.** Measured slip characteristic.

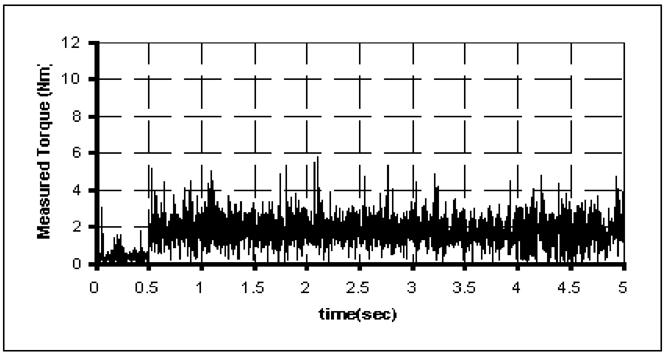

**Fig 8c.** Measured load torque.

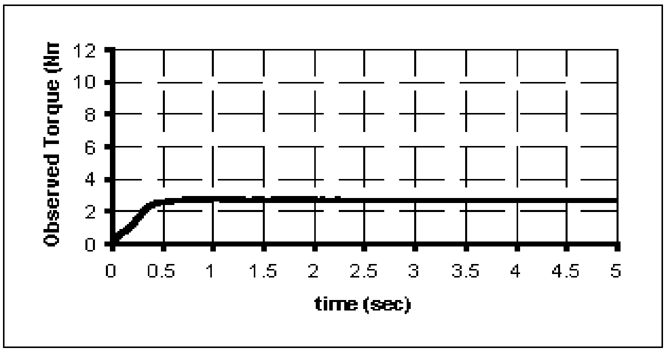

**Fig 8d.** Measured observed torque.

**Figure 8.** Simulation and measured results at 33V phase voltage, which is analogous to an icy surface of 0.2 $\propto$.

From the measured data, it can be seen that the incorporation of the fuzzy-based discrete-time observation technique allows the dynamic $\propto$-$\sigma$ characteristics to be obtained without a-priori knowledge of '$\propto_{max}$' (Figure 2).

## VI. CONCLUSION

In this paper a low-cost experimental test bench to facilitate the evaluation for ABS/ traction control (TC/ABS) algorithms, for application on-board electrically powered vehicles, was developed. It was shown that employing an induction motor as a load for the drive-train enabled various tire/road $\propto$-slip characteristics could be simulated, thereby enabling rapid algorithm development with minimal time and cost. The feasibility of using a fuzzy technique for real time steady state control of vehicles was investigated. It was found that the fuzzy controller is capable of compensating for nonlinearities as compared to 'bang-bang' limited control. The robustness of the fuzzy controller is impressive. The results have indicated that Fuzzy Logic based ABS / traction control could substantially improve steady state longitudinal performance and offer a potential for optimal control of driven wheels, under icy road conditions.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the UK Engineering and Physical Sciences Research Council for providing research studentship to Ms.Khatun.

## REFERENCES

[1] Howell, S., *'Traction Control for an Electric Vehicle'*, Final Year MEng Project, Dept. of EEE, University of Sheffield, 2000.

[2] Harned,J.L., Johnstine, L.E., Scharpf,G., *'Measurement of tire brake force characteristic as related to a wheelslip (antilock) control system'*, SAE Trans,vol 78, No. 69214, 1969.

[3] Ray,L.R., *'Non linear system and tire force estimation for advanced vehicle control'*, IEEE Trans on Control Systems Technology, vol 3, No.1, 1995.

[4] Klien,R., *'Antilock Braking System and Vehicle speed estimation using Fuzzy Logic'*, FuzzyTECH Application paper, http://www.fuzzytech.com/, 1999.

[5] Constantin V.A., *'Fuzzy Logic in Automotive Engineering'*, Embedded Systems Conference, 1996.

[6] Robinson, B.J., *'A study of various car antilock braking system'*, Research Report 340, Department of Transport and Road Research Laboratory, UK, 1991.

[7] Mellor,P.H., Scofield,N., Hor,P.J., *'Brushless permanent magnet drives for all-electric racing karts'*, Proc.29th Int. Symposium on Automotive Technology Automation, 1996.

[8] De Koker,P.M., Gouwes,J., Pretorius,L., *'Fuzzy Control Algorithm for automotive traction control'*, IEEE Trans on Industrial Applications in Power Systems, Computer Science and Telecommunication, vol 1, 1996.

[9] Khatun P, Bingham C M, Schofield N, Mellor P H: *'Antilock-braking/Traction Control for a High-Performance All-Electric Racing Vehicle'*, 41st International Conference PCIM for Power Conversion and Intelligent Motion, Nuremburg, Germany June 22-24, 1999.

[10] Khatun,P., Bingham,C.M., Mellor,P.H., *'Comparison of control methods for Electric Vehicle Antilock Braking / Traction Control systems'*, SAE 2001 World Congress, Detroit, USA, paper no.: 2001010596, March 2001.