Design and simulation of an ABS for an integrated active safety system for road vehicles

Murat Sahin

TUSAS Aerospace Industries Inc.,
ODTU Teknokent TAI A-Blok,
06531, Ankara, Turkey
E-mail: mtsahin@gmail.com

Y. Samim Ünlüsoy*

Mechanical Engineering Department,
Middle East Technical University,
06531, Ankara, Turkey
E-mail: unlusoy@metu.edu.tr
*Corresponding author

Abstract: A design methodology for an anti-lock braking system (ABS) controller for four-wheeled road vehicles is presented. In the study, a flexible approach was adopted considering integration with an integrated active safety system control structure. In the hierarchical control strategy proposed for the ABS controller, a high-level controller, through vehicle longitudinal acceleration-based estimation, determines reference wheel slip values, and a low-level controller attempts to track these reference slip signals by modulating braking torques. Two control methods were investigated for the design of the low-level controller: fuzzy logic control and PID control.

Keywords: anti-lock braking system; ABS; active safety systems; fuzzy logic control; PID control; vehicle model; design; simulation; integrated active safety system; road vehicles.

Reference to this paper should be made as follows: Sahin, M. and Samim Ünlüsoy, Y. (2010) 'Design and simulation of an ABS for an integrated active safety system for road vehicles', *Int. J. Vehicle Design*, Vol. 52, Nos. 1/2/3/4, pp.64–81.

Biographical notes: Murat Sahin received his MSc and BSc in Mechanical Engineering from the Middle East Technical University, Ankara, Turkey. He is presently working in the aerospace industry.

Y. Samim Unlusoy received his BSc and MSc in Mechanical Engineering from the Middle East Technical University, Ankara, Turkey. He received his Doctorate in Mechanical Engineering from Birmingham University, UK. He has taught in various universities in Turkey and abroad. He is a Professor of Mechanical Engineering in the Middle East Technical University. His current research areas include automotive engineering, vehicle dynamics, and control systems.

1 Introduction

Active safety concept has its roots in the early applications of anti-lock braking. The idea, however, became popular with the implementation of electronically controlled anti-lock braking systems (ABS) in luxury sedans in the late '70s. In the following years, along with technological advances and increasing demand for road safety, the systems were improved and new safety enhancement technologies such as electronic brake distribution and active yaw control systems were introduced. The need for providing these individually developed technologies together in passenger cars has resulted in the concept of integration of the active safety systems, commercially realised with the common name of electronic stability program (ESP). ABS, as an important part of this new structure, maintains its importance and its design requires further attention in regard to integration with other active safety systems.

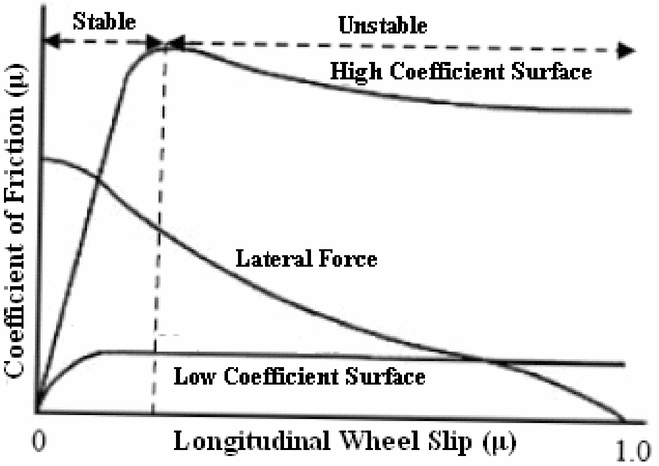
The objective of an ABS controller is basically to provide retention of vehicle directional control capability and if possible, shorter braking distances by controlling the wheel slip during braking.

Almost all ABS control schemes in literature are based on the control of longitudinal wheel slip. Longitudinal wheel slip or tyre braking slip, λ, is defined as the difference between vehicle velocity component in the plane of the tyre and wheel circumferential velocity, normalised with respect to component of vehicle velocity in the plane of the tyre.

$$\lambda = \frac{V_w - \omega \cdot R}{V_w} \tag{1}$$

The importance of the longitudinal wheel slip can be understood from the typical longitudinal coefficient of friction μ versus slip curve provided in Figure 1 (Kazemi et al., 2005). In order to achieve directional stability, lateral forces must be considered. As can be inferred from the figure, lateral coefficient of friction and hence, lateral force decreases with increasing longitudinal slip, reaching absolute zero at wheel lock.

Figure 1 Longitudinal coefficient of friction (μ) vs. longitudinal wheel slip (λ)



Source: Kazemi et al. (2005)

Longitudinal coefficient of friction versus longitudinal slip graph may be divided into two regions. Friction process is stable in the first linearly increasing part including the peak point and at the 100% slip point (Limpert, 1992). Decreasing part of the curve is unstable and unless braking force is reduced in time, longitudinal wheel slip increases very rapidly and wheel lock becomes unavoidable. ABS control system acts by limiting slip values to the stable region to prevent wheel lock.

By selecting a slip ratio in the vicinity of the point corresponding to the peak longitudinal coefficient of friction, maximum use of the available friction can be achieved, which results in shorter braking distance. It should also be noted that the wheel slip ratio, for which the peak longitudinal friction force is obtained, increases with increasing tyre slip angle; but lateral force generating capability of tyres decreases for higher longitudinal wheel slip. Therefore, in the case of cornering while braking, there is certainly a compromise between braking performance and manoeuvrability of the vehicle.

Various methods were proposed in literature for ABS controller design; the majority of the control strategies are based on fuzzy logic control (Layne et al., 1993; Madau et al., 1993; Mauer et al., 1994; Mirzaei et al., 2005; Yu et al., 2002) and sliding mode control (Buckholtz, 2002a; Drakunov et al., 1995; Lee and Sin, 2000). ABS controller design is a challenging work because of the non-linear tyre behaviour, time-varying characteristics of the braking system, and environmental influences. Road surface condition is a serious problem for the controller as an environmental disturbance factor. ABS controller irrespectively must maintain adequate performance on different road conditions with various μ-slip curves. There exists also a high uncertainty in estimation of longitudinal wheel slip, or more correctly the vehicle velocity in the tyre plane.

Conventional ABS controllers utilise a rule-based method to maintain longitudinal wheel slip in a certain range on the information provided by angular wheel speed sensors. The generic control approach is based on wheel slip and angular acceleration control (Petersen, 2003). The principle of the algorithm implemented in conventional ABS is based on limited cycling of longitudinal wheel slip in a desired range. The algorithm sets certain bounds for wheel angular acceleration and wheel angular speed and uses a complex rule set to decide for the pressure mode of the actuator (Bowman and Law, 1993; Bosch, 1995). The control is known to be highly adaptive to uncertainties in tyre force characteristics and the friction coefficient; however, the oscillatory nature of the conventional ABS is undesirable due to noticeable vibrations and resulting performance limitations (Petersen, 2003). Due to its complex structure, the design also provides only limited flexibility for integration and further improvements in integrated systems.

2 Modelling

In this study, a mathematical eight degrees of freedom (DOF) non-linear vehicle model was constructed in MATLAB/Simulink software environment to replace the real vehicle for the development and performance analysis of the ABS controller. A non-linear tyre model from the literature was used for the study.

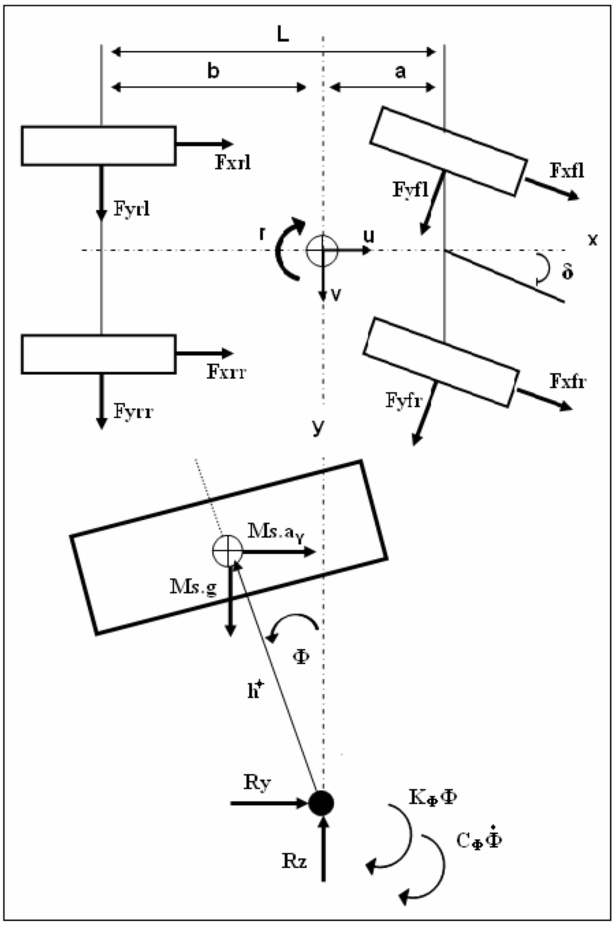
2.1 Tyre model

The tyre model used in this study is based on the work of Allen et al. (1987). Allen tyre model is a non-linear model based on an analytical study, which makes use of experimentally obtained parameters. The model allows the simulation of cases where longitudinal and lateral tyre forces are simultaneously applied and it is therefore a proper choice considering the objectives of this study.

2.2 Vehicle model

A non-linear eight DOF vehicle model was constructed, which includes longitudinal, lateral, yaw and roll DOF together with motion of four independent wheels. The model allows the simulation of the vehicle motion in roll direction and takes account of lateral weight transfer. The governing differential equations of motion were derived for a body fixed reference frame located at the centre of gravity of the vehicle according to the model shown in Figure 2.

Figure 2 Vehicle model



$$\begin{aligned} M\cdot a_X &= \left(F_{xfl}+F_{xfr}\right)\cdot\cos\delta_f-\left(F_{yfl}+F_{yfr}\right)\cdot\sin\delta_f+F_{xrl}+F_{xrr}\\ a_X &= \dot{u}-v\cdot r \end{aligned} \tag{2}$$

$$\begin{aligned} &M\cdot a_Y+M_S\cdot h'\cdot\ddot{\phi}\cdot\cos(\phi)=\left(F_{yfl}+F_{yfr}\right)\cdot\cos\delta_f\\ &+F_{yrl}+F_{yrr}\left(F_{xfl}+F_{xfr}\right)\cdot\sin\delta_f\\ &a_Y=\dot{v}+u\cdot r \end{aligned} \tag{3}$$

$$\begin{aligned} &I_{ZZ}\cdot\dot{r}=a\cdot\left[\left(F_{xfl}+F_{xfr}\right)\cdot\sin\delta_f+\left(F_{yfl}+F_{yfr}\right)\cdot\cos\delta_f\right]\\ &-b\cdot\left[F_{yrl}+F_{yrr}\right]+\frac{t}{2}\cdot\left[F_{xrl}-F_{xrr}\right]+\frac{t}{2}\cdot\left[\left(F_{xfl}-F_{xfr}\right)\cdot\cos\delta_f+\left(F_{yfr}-F_{yfl}\right)\cdot\sin\delta_f\right] \end{aligned} \tag{4}$$

The vehicle was modelled as an arrangement of three rigid bodies: the sprung mass and front and rear unsprung masses. The sprung mass interacts with unsprung masses by front and rear suspension systems. The roll stiffness and roll damping of the suspensions are assumed to be constant for the whole range of roll motion. The roll axis is defined as the line connecting roll centres, around which sprung mass rotates. The roll centre locations are assumed not to change during vehicle motion. In the equations, K_ϕ and C_ϕ represent respectively the roll stiffness term and total roll damping.

$$I_{XX}\cdot\ddot{\phi}=M_S\cdot g\cdot h'\cdot\sin\phi-M_S\cdot a_Y\cdot h'\cdot\cos\phi-K_\phi\cdot\phi-C_\phi\cdot\dot{\phi} \tag{5}$$

Normal loads for each wheel can vary due to longitudinal and lateral load transfers. For front inner wheel, normal load expression in a turn is stated below.

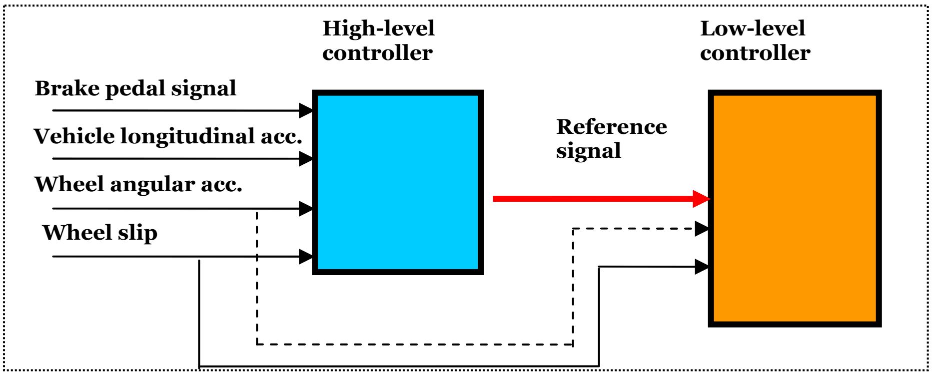
$$\begin{aligned} &F_{zfi}=\frac{W}{2}\cdot {}^{b}\!/_{L}-{}^{1}\!/_{2}\cdot M\cdot a_X\cdot {}^{h}\!/_{L}-K_R\cdot\\ &\left[M\cdot a_Y\cdot\frac{h}{T}+M_S\cdot h'\cdot\ddot{\phi}\cdot\frac{h}{T}-M_S\cdot g\cdot\frac{h'}{T}\cdot\sin\phi\right] \end{aligned} \tag{6}$$

3 Controller design

The proposed ABS controller structure is composed of two subcontrollers: a high-level controller and low-level slip controller. The hierarchical structure was adopted considering easy adaptability to integration with an integrated active safety system controller. ABS control is maintained individually for each wheel through independent controller modules of both subcontrollers. The operation of the designed ABS is basically as follows: The high-level controller sensing the impending lock at a wheel through the inherent initiation logic dispatches a reference slip signal, which is then received by the low-level wheel slip controller. The low-level controller modulates braking torque at the corresponding wheel independently in order to track this reference signal.

The two-stage ABS controller was designed to have a single data transfer in between for each wheel. The reference slip signal as the single output of the high-level controller includes the information for the initiation of the ABS control at the corresponding wheel in addition to the reference slip data that is necessary for the low-level slip controller. Inputs to the ABS controller are vehicle longitudinal acceleration, brake pedal on/off signal, wheel angular accelerations and longitudinal slips of each wheel. The proposed ABS controller structure is shown in Figure 3.

Figure 3 Proposed ABS controller structure (see online version for colours)



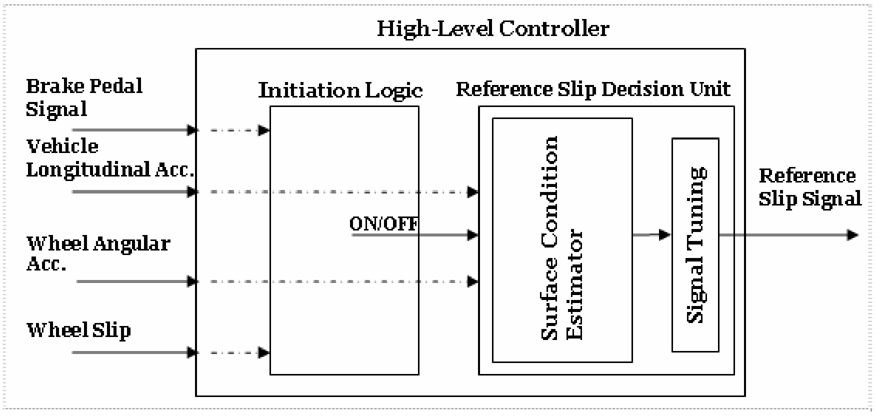
3.1 High-level controller

The duty of the high-level controller is to set the reference slip values which will be attained by the low-level slip controller. In the design of the high-level controller, there were some points which constituted the base of the work. For the purpose of showing the approach followed for the design, these are summarised as below.

- The controller is expected to be flexible such that it can adapt to different road conditions and driver inputs and provide reliable and satisfactory information to the low-level slip controller.
- In a braking situation without steering, the priority of the controller is to maintain the longitudinal wheel slip at a point that gives the peak value of longitudinal coefficient of friction in the μ-slip curve, in order to obtain the maximum braking force from road surface, thus the minimum stopping distance. The road condition must be taken into account to achieve the optimum longitudinal wheel slip value.
- For the case of braking with turning, the complex relationships between longitudinal brake force and side traction must be taken into account.
- The high-level controller must be designed to operate with different sublevel slip controllers and therefore is expected to work well for different performance outputs.

In the design of the controller, the above mentioned points were taken into account. High-level controller takes brake pedal on/off signal, longitudinal acceleration, longitudinal slip and wheel acceleration information for each wheel. The controller is composed of two function blocks: ABS initiation logic and reference slip decision unit. Structure of the high-level controller is depicted by the representative diagram provided in Figure 4.

Figure 4 High-level controller structure



ABS initiation logic was realised in MATLAB/Simulink by a Stateflow® block. ABS initialises when longitudinal slip at the corresponding wheel reaches a certain threshold and if brake pedal is pressed at the same time. Note that ABS operates only when braking is present; therefore, as soon as the driver releases brake pedal, control is switched off.

Reference slip decision unit takes longitudinal acceleration, output signal of the ABS initiation logic block and wheel angular acceleration signal as inputs. The block incorporates a fuzzy logic based surface condition estimator and a Stateflow block for tuning the signal according to wheel angular acceleration information. The only input of the estimator system is the longitudinal acceleration of the vehicle.

Estimation of the longitudinal coefficient of friction, μ, from vehicle longitudinal acceleration can give reasonable results in the ABS operation range. There are studies in literature which use longitudinal acceleration as a parameter in the identification of road condition (Bowman and Law, 1993; Kazemi et al., 2005; Yu et al., 2002). Following from the equations of motion, longitudinal acceleration is basically a function of braking force. Since wheel slip can be maintained in a certain range when ABS is active and assuming effect of changes in normal load and vehicle velocity variation is negligible in tyre braking force development, longitudinal acceleration can be used to predict nominal surface coefficient of friction. In the proposed design, vehicle longitudinal acceleration information is used directly as an estimate of road condition and is the input to the fuzzy logic block which is designed to output a reference longitudinal slip value that is close to the peak of the μ-slip curve of the identified surface for zero slip angle. The design simply maps vehicle longitudinal acceleration as a surface friction coefficient estimate to predetermined reference slip values which provide highest braking force in straight-line driving.

Reference slip decision unit in the high-level controller was designed to output the reference slip according to same fuzzy rules and membership functions regardless of the steering manoeuvres. Note that this design favours lateral performance due to the effect of sideslipping on tyre force characteristics. Peak of the μ-slip curve shifts to right as slip angle increases while side friction force decreases with increasing longitudinal wheel slip; therefore by keeping the reference slip constant in steering, the proposed design preserves the lateral force generation capability of the tyre.

3.2 Low-level controller

The task of low-level controller is basically to maintain the longitudinal slip value at a wheel close to the reference slip signal, i.e., track the reference slip, by modulating brake torques accordingly. In this study, two controller designs are proposed for this purpose: Fuzzy logic controller and PID controller.

The output of both low-level slip controller alternatives was chosen to be the rate of change of brake torque applied at wheels, as it would be proper in the case of a hydraulic actuator. Although the brake system was not modelled in order to realise a flexible design, it was necessary to have a logical and physically realisable controller output for the application. For this reason, the output of the controller was also selected to be on the order of attainable hydraulic pressure change rates in other studies (Schürr and Dittner, 1984; Yazicioglu, 1999). More precisely, the actuator is thought to be able to deliver braking torques at any rate continuously between –30,000 N.m/s and 30,000 N.m/s without time delay. Note also that, when required, the control system can be adapted to a customary hydraulic brake system by scaling the output of the controller and using these scaled values through a post-processing block to decide for the on-off times of the valves as in the study of Madau et al. (1993).

3.2.1 Low-level fuzzy logic control

The low-level fuzzy logic controller was designed to take longitudinal wheel slip error and wheel angular acceleration as inputs and return brake torque change rate as output. The wheel slip error is defined to be the deviation of the actual longitudinal slip from the reference signal sent by the high-level controller. The controller was designed using Mamdani type fuzzy inference method and input variables and output are each realised by five membership functions. Fuzzy rules and membership functions are same for all road conditions. Fuzzy sets are shown in Figures 5, 6 and 7.

Figure 5 Fuzzy set for longitudinal wheel slip error

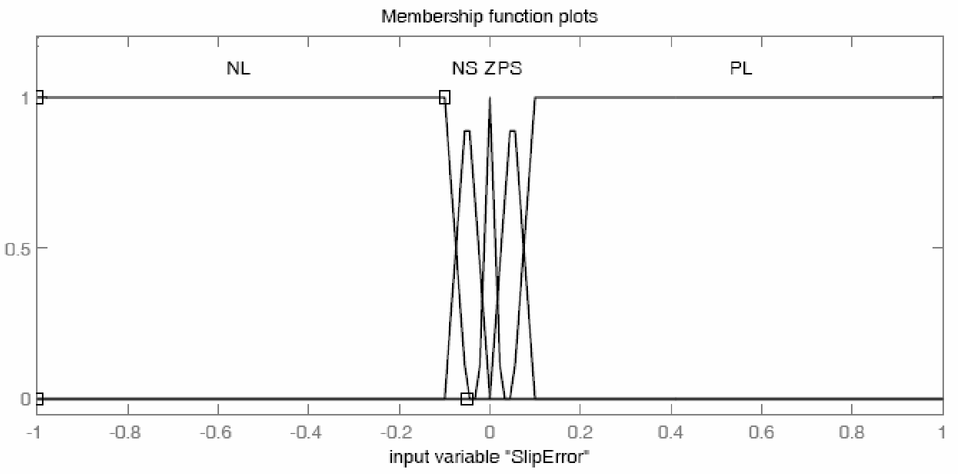


Figure 6 Fuzzy set for wheel angular acceleration

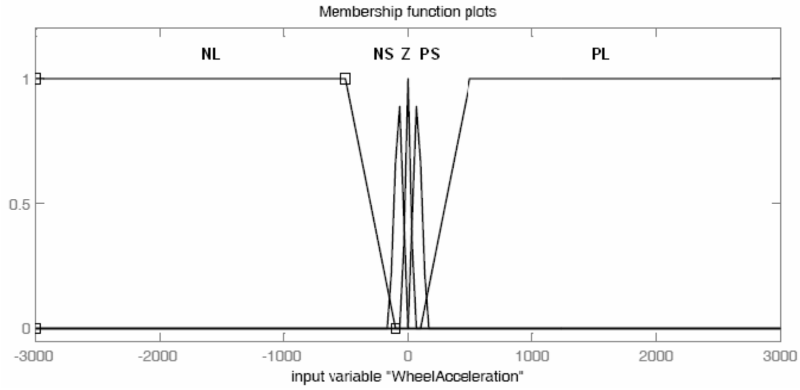
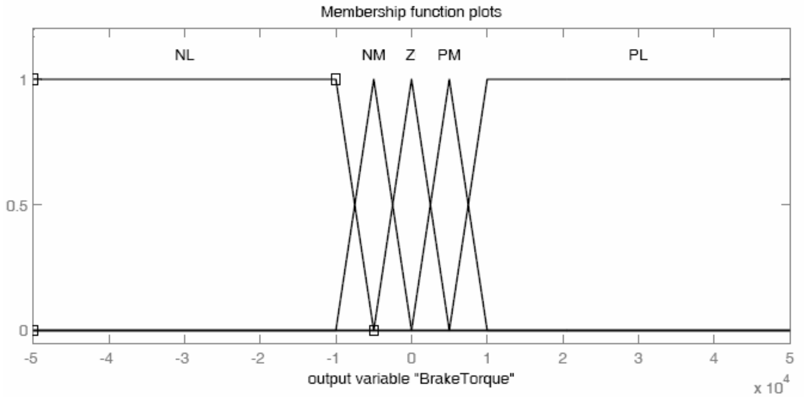


Figure 7 Fuzzy set for brake torque change rate



Final design of the fuzzy controller was attained following a lengthy trial and error process and an intense study regarding analysis of simulation results. For sufficiently large wheel angular acceleration values, the rule base (see Table 1) was designed to reduce baking torque at the maximum allowable rate, irrespective of the wheel slip ratio, to reduce the initial wheel slip overshoot insofar as it is possible; on the other hand, the controller was designed to output a gradually decreasing braking torque change rate when angular deceleration drops below a certain limit, to prevent the cycling of the wheel slip observed following the recovery from the initial slippage increase.

Table 1 Fuzzy logic controller rule base

λ / ω	*PL*	*PS*	*Z*	*NS*	*NL*
PL	Z	NM	NL	NL	NL
PS	Z	Z	NM	NL	NL
Z	PL	PM	Z	NM	NL
NS	PL	PM	PL	PL	NL
NL	PL	PL	PL	PL	NM

3.2.2 Low-level PID controller

The controller takes the error between longitudinal wheel slip and the reference slip signal as the only input and attempts to reduce this error through generating a corrective action, limited brake torque change rate, based on the three control parameters. The design of the PID controller was not based on an analytical approach; controller parameters were determined following an intensive simulation study and detailed analysis of results. In the design, it was first desired to minimise the overshoots observed at the initiation of the hard braking and during transition between different surfaces and a small settling time was important for fast recovery from slippage and adaptation; therefore, it was decided to have a weighted derivative gain; however, integral action was also necessary for a faster response and a satisfactory steady-state performance; for that reason, a slight increase of overshoot and oscillations were tolerated.

3.3 Measurement and estimation of states

The proposed ABS controller requires longitudinal acceleration information of the vehicle, longitudinal wheel slips and angular acceleration data of wheels for operation. For vehicle acceleration, a longitudinal accelerometer, mounted at centre of gravity, is necessary and an estimate of wheel angular acceleration can be obtained through standard rotational wheel speed sensors; however, in calculation of wheel slips, there exists a considerable uncertainty and in literature, the subject was discussed extensively.

In order to calculate longitudinal wheel slip, the longitudinal velocity of the tyre in the plane of the tyre is required. Various schemes are proposed in literature for wheel slip estimation; most of them ignoring the lateral effects in cornering, focused on estimation of absolute vehicle speed. The longitudinal tyre velocity in the tyre plane and thus, wheel slip can be, in fact, directly calculated. The calculation requires longitudinal and lateral acceleration of the vehicle at centre of gravity, yaw rate and steering wheel angle, all of which can be measured directly through sensors of an integrated active safety system. In this study, it is thought that the proposed ABS controller can benefit from the sensor hardware of the integrated active safety system and the measured signals are processed through appropriate filtering methods before transmitted to ABS. For design and simulation purposes throughout the study, this direct state calculation method was adopted in this framework, with data obtained from vehicle dynamics modelled in MATLAB/Simulink. However, for the purpose of demonstrating the applicability of the controller in the presence of noisy measurements, a Kalman filter estimation method was also developed based on the work performed by Watanabe et al. (1992). The scheme estimates absolute vehicle velocity from noisy vehicle longitudinal acceleration data and wheel angular speed. The method incorporates a rule-based strategy, which switches the values of covariance matrices during slippage of the wheel from which the measurement is taken.

4 Simulations

The simulation study includes straight-line braking and combined braking and steering tests for different road conditions. In these simulations, the results for both low-level slip controller alternatives were compared and discussed for each case. Performance of the ABS was tested for noisy measurement data as well.

4.1 Straight-line braking case

It is clear that for this case, driver's aim is to stop the vehicle or reduce the vehicle speed to such a level to avoid a possible accident. In such a situation, naturally, driver expects from a vehicle safety enhancement system to assist in order to achieve the maximum available deceleration; on the other hand, an ABS control system must regulate wheel brake torques to preserve lateral control capability at any instant since the controller cannot know the intention of the driver beforehand. It should be underlined that achieving minimum stopping distances is not the primary concern in almost all ABS designs and this study is not an exception. However, proposed ABS controller's priority is to achieve maximum braking efficiency for straight-line braking case since the high-level controller irrespectively sets a reference longitudinal slip value that is close to the peak of the μ-slip curve of the identified surface for zero slip angle as mentioned before.

For the simulation, it was assumed that the vehicle was moving at 90 km/h on a level road, when the braking action was initiated. A total braking torque of 6000 Nm was applied to the vehicle, distributed 70:30 between front and rear axles. Front-to-rear torque distribution proportioning was purposely arranged so that front-axle wheels lock before rear-axle wheels to maintain stability and in selecting the ratio, maximum braking performance was also considered.

In Figures 8 and 9, simulation results for wet-asphalt road case are shown. While in the uncontrolled case, front and rear-axle wheels lock under 0.3 seconds, for both low-level slip controller alternatives, lock-up was prevented and following an initial overshoot, wheel slip-ratio of the wheels rapidly reached reference slip values at steady-state. System response is similar for both fuzzy logic and PID low-level slip controllers. For fuzzy controller, a short small transient oscillatory response can be observed; however, in the case of PID controller, such oscillations were eliminated due to weighted derivative action.

Figure 8 ABS performance on wet-asphalt road for low-level fuzzy logic controller (see online version for colours)

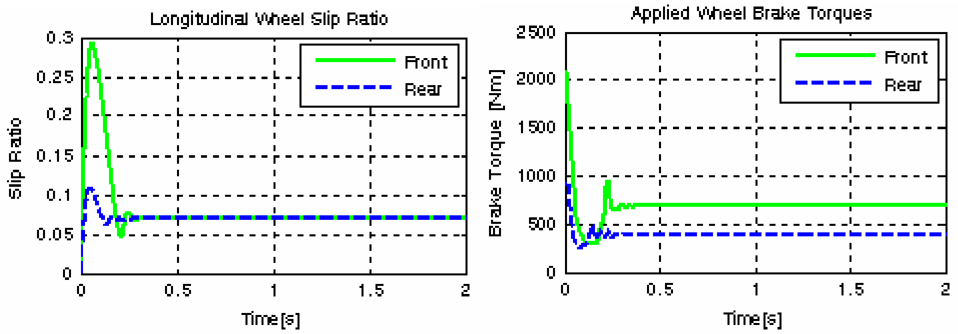
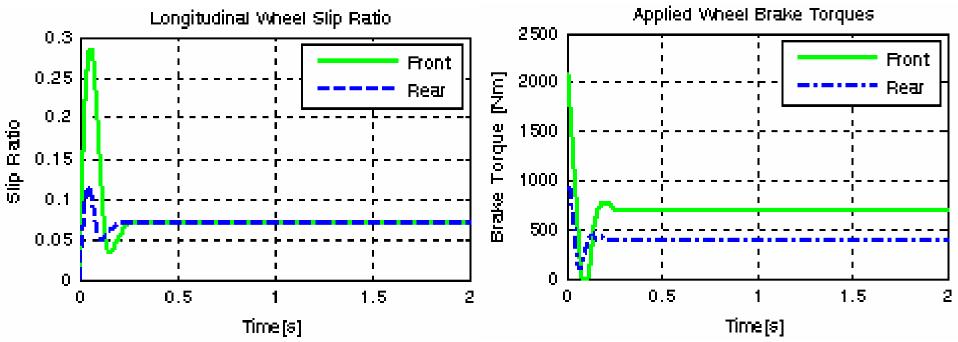


Figure 9 ABS performance on wet-asphalt road for low-level PID controller (see online version for colours)

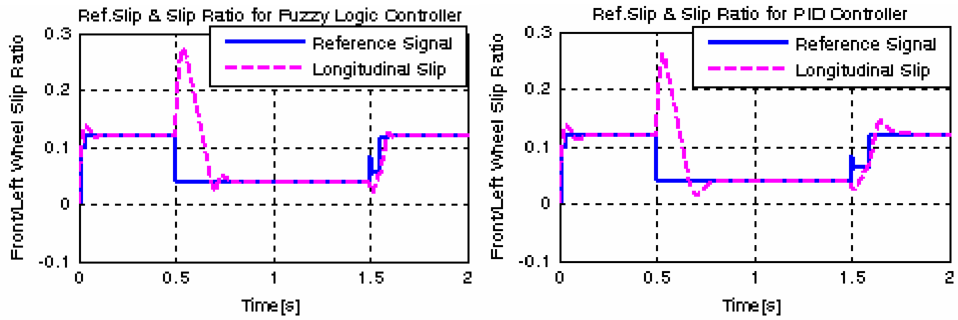


Following initiation, both low-level slip controllers try to decrease the brake torques for each wheel at the maximum rate possible. The initial overshoot of approximately 30% slippage is due to the limited brake torque change rates regardless of the control method.

The slip ratio of the front axle wheels is higher compared to the rear wheels because of the initial front-to-rear brake torque proportioning. For both low-level controllers, the recorded braking distance on wet asphalt road is 17 metres shorter when compared to the uncontrolled case. On dry asphalt with the same initial conditions, this distance is 8 metres.

Simulations were also conducted for a road condition that has surface friction transitions. For the test, the road surface is thought to be divided into three segments. Initially, the road is emulated as dry asphalt having 0.9 coefficient of friction for the first half second of simulation. From $t = 0.5$ to $t = 1.5$ seconds, the road segment is icy road with 0.2 coefficient of friction and changes again to the dry asphalt road for the rest of the simulation time. The initial velocity of the vehicle is chosen to be 90 km/h, the same as in the previous simulations.

Figure 10 ABS performance for low-level fuzzy logic and PID controllers (see online version for colours)

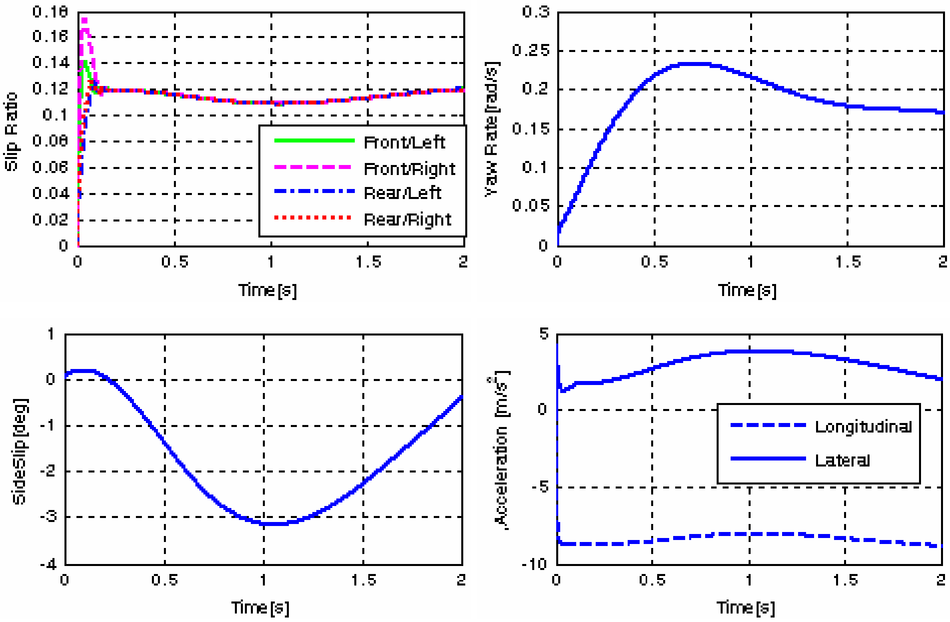


In Figure 10, slip ratio developments of the front/left wheel are depicted with the generated reference signals. In the plots, it can be observed that the ABS controller shows successful performance in adapting to changes in road surface conditions for both low-level slip controllers. Low-level controllers reacted to the changing reference signal upon transition from dry to icy road by rapidly decreasing the braking torque. Upon transition from icy road back to dry asphalt, due to limited braking torque change rates, the low-level controller failed to attain the required brake torque levels; however, this had little effect of braking performance. High-level controller detects the surface transition from the provided longitudinal acceleration information and sets the new reference slip signal accordingly. Despite the slightly degraded performance upon transition from icy road back to dry asphalt, the condition identifier logic was successful and the high-level controller provided the reference signals necessary for maximum braking efficiency.

4.2 Combined braking and steering case

The case is the likely scenario of an emergency braking situation in which the driver intends to avoid the collision by steering away from the obstacle while also applying heavy braking at the same time in an attempt to reduce the severity of a possible crash at the least. ABS controller is expected to preserve directional control by ensuring the development of sufficient lateral tyre force at wheels under heavy braking conditions. In Figure 11, response of the ABS controlled vehicle is depicted. When cruising with an initial speed of 90 km/h on dry asphalt road ($\mu = 0.9$) at $t = 0$, 6° step steering angle input is applied simultaneously with 6000 Nm brake torque with 70:30 front to rear ratio. The plot is generated for the low-level fuzzy logic slip controller; for the PID controller case, the response is similar.

Figure 11 ABS controlled vehicle response for combined braking and steering case (see online version for colours)



ABS controller successfully preserved directional stability of the vehicle, in this case, by controlling wheel slip. The plots show that vehicle response has an understeer character. This degraded lateral response is inevitable due to the limited tyre lateral force margin left in braking; however, the understeer situation is more manageable for the average driver compared to an oversteer case and application of a larger steering input can compensate the lost lateral movement.

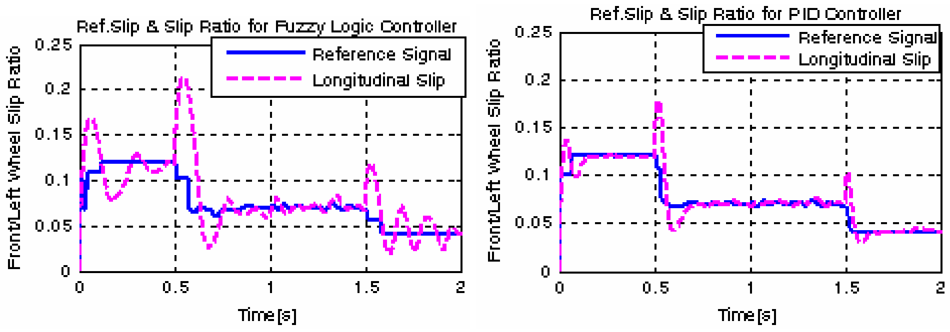
For this case, wheel slip was developed different for each wheel due to lateral load transfer; maximum overshoot of the front/left wheel slip response, though seems at an elevated level, does not have an adverse effect on braking performance. The noticeable deviation of the slip ratio at around $t = 1$ s is a result of a misinterpretation of surface condition of high-level controller due to influence of steering; however, it serves to increase lateral movement margin here. Indeed, the high-level controller indirectly leaves the initiative to the driver in setting the optimal reference slip signal; the controller favours principally manoeuvrability over stopping distances in the presence of steering and braking force decreases in proportion to steering intensity. The effect of lateral acceleration generated by cornering on longitudinal acceleration and hence braking efficiency can be seen also in Figure 11.

4.3 Performance of the ABS controlled vehicle for noisy measurement data

Performance of the ABS controller was tested for noisy measurement data as well. The system uses the Kalman filtering method, described previously, to estimate the vehicle speed, which is required for calculation of longitudinal wheel slip. Only inputs of the ABS controller are wheel angular velocity and longitudinal vehicle acceleration which are modelled as normally distributed white noise with zero mean and have noise variances of 0.05 rad^2/s^{-2} and 0.80 m^2s^{-4} respectively.

The road surface for the study has a dry asphalt segment ($\mu = 0.9$) for the first half second of the drive, between $t = 0.5$ s and $t = 1.5$ s surface has wet asphalt road property ($\mu = 0.5$) and for the rest, road surface is icy ($\mu = 0.2$). The chosen road profile is ideal to observe the vehicle response at the three different road conditions and evaluate the adaptation performance of the controller to changing friction levels. A total braking torque of 6000 Nm with 70:30 front/rear ratio was applied at the start to a vehicle-driven in a straight-line with 90 km/h initial velocity.

Figure 12 Response of the ABS controlled vehicle for noisy measurement data (see online version for colours)



In Figure 12, slip response of the front axle wheels are plotted with the generated reference slip signals for fuzzy logic and PID low-level slip controller alternatives. Especially for the fuzzy logic low-level controller, the oscillatory wheel slip response is noticeable; on the other hand, following the overshoots at the transition points, average slip is very close to the reference slip signal and despite the degraded performance, the controller is obviously successful since it manages to limit the cycling in a certain margin. Note also that high-level controller produced a reference signal with ideal slip values for the corresponding surface conditions.

5 Integration with an integrated active safety system

Integrated active safety system concept is the last stage of the development of vehicle safety enhancement technologies. It is basically integration of previously developed individual systems under one roof. Despite the usually conflicting objectives of integrated control with flexible marketing strategies of supplier companies, the concept offers promising benefits that cannot be overlooked and there are increasing efforts towards systems integration in vehicle active safety applications. Integrated active safety system approach can reduce complexity of the overall system, avoid costly duplication of hardware components and prevent unexpected interactions between subsystems which are mostly due to results of the traditional add-on approach in design. Through achieving control coordination, it is also possible to enhance performance of the previously individually operated systems (Unlusoy et al., 2006; Gordon et al., 2003; Schilke et al., 1989).

The task of the proposed ABS controller is formulated as dynamic reference slip tracking where a high-level subcontroller determines the reference longitudinal wheel slip ratio according to changing road conditions and a low-level subcontroller system attempts to track this signal through modulating brake torque. The structure provides a highly flexible platform for integrated control with other active safety enhancement control systems and in particular with wheel braking based active yaw stability control. In determination of the reference slip, coordinated decision-making may contribute to achieve a vehicle response along driver demands and the low-level controller can be used directly as a part of a yaw stability control system.

The concept of the adopted hierarchical control structure in the study is actually based on the idea that decisions about the dynamic behaviour of the vehicle should be made at a high-level considering driver preferences and in a unified manner with different vehicle dynamics control systems. In combined braking and steering manoeuvres, coordination of ABS with an active yaw stability control system may result in a vehicle dynamic response closer to the intention of the driver. In current production ABS systems and in literature, directional control is defined as a main objective; however, control algorithms work irrespective of the steering input and thus driver request or any other parameter regarding lateral response of the vehicle. A yaw stability controller calculates an ideal yaw rate value representing intended course of the driver for operation and this information can be shared with the high-level controller of the proposed ABS. Reference slip for the wheels may be chosen specifically to generate a brake moment in the direction of the path considering the understeer behaviour in ABS operation observed in the presented simulation study. On the other hand, braking force should be maximised as much as possible as well. In such a case, the priority or weighting is decided according to predicted driver intention. A simpler application is to reduce directly reference slip values according to comparison of actual and desired yaw rate to increase the lateral generation capability of the tyres at the cost of a lengthened stopping distance. In either case, a study regarding analysis of driver behaviour in emergency braking manoeuvres is definitely necessary and pre-crash systems may be helpful in assessing the situation as well.

The duty of the low-level controller is basically to track the reference slip signal sent by the high-level controller through modulating brake torque at the corresponding wheel. Reference wheel slip assignment method is also appropriate for wheel braking based yaw stability control. Buckholtz (2002b) uses reference slip assignment for each corner of the vehicle to track a desired yaw rate. The proposed low-level controller can be readily employed for this purpose as well. In the supervision of a coordination logic block or master controller, wheel braking based active yaw stability control can intervene when it is necessary by simply dispatching reference slip signals directly to the low-level slip controller of each wheel individually. By reference slip tracking, yaw stability control also ensures the prevention of wheel lock since the low-level controller can maintain wheel slip at every point of the μ-slip curve.

In a unified structure, the low-level controller is positioned as a common lower level module where ABS and active yaw controller, in interaction, determine and assign reference wheel slips as high-level functions. Natural extension of this structure is a fully centralised control. This model requires a specific design for an active yaw controller based on reference slip tracking and a single low-level controller for actuator is not preferable considering failure management issues in case of failure of the communication link or the low-level controller. A more decentralised control approach can provide redundancy for failsafe operation and is easier to implement. In this configuration, active yaw controller uses the low-level ABS controller only as an explicit function to prevent wheel slippage exceed beyond a certain threshold while it modulates braking torques independently to track desired yaw dynamics. A coordination algorithm constantly monitors longitudinal wheel slip and switches control when a certain slip ratio is reached and wheel slippage is maintained at that point by merely sending the signal as a reference to the low-level controller. In this case, wheel braking torques is directly adjusted by the low-level controller of ABS. The coordination logic may return control to normal operation when the yaw controller demands a wheel braking torque level lower than the torque applied by the low-level ABS controller. For yaw control, it is desirable to limit the wheel slippage to the linear range of the μ-slip curve in which case the reference threshold should be around the peak. A more predictable control is achieved by this way; however, a μ estimation algorithm is necessary for this application.

6 Conclusions

In this paper, a design methodology of an ABS controller for four wheeled road vehicles is presented with a detailed simulation work. In the study, it is intended to follow a flexible approach for integration within unified control structure of an integrated active safety system. A hierarchical control structure was adopted for the controller and the applied strategy was formulised as reference slip tracking. The two low-level controller alternatives (fuzzy logic and PID) successfully tracked the reference slip values determined through vehicle longitudinal acceleration based surface condition estimation for different road conditions. In simulations, for straight-line braking case, a considerable improvement in stopping distances was achieved. In combined braking and steering case, the stability was maintained; on the other hand, an understeer vehicle response was observed due to limited lateral force generation capability as expected. By benefiting from the sensory hardware of the integrated active safety system, a more precise calculation of the wheel slip was attained, which provided the low-level controllers a successful tracking ability of the reference slip signal. Performance of the ABS controlled vehicle was also simulated for noisy vehicle acceleration and angular wheel speed data.

References

Allen, R.W., Rosenthal, T.J. et al. (1987) 'Steady state and transient analysis of ground vehicle handling', *SAE* Paper 870495.

Bosch, R. (1995) *Bosch Automotive Brake Systems*, Stuttgart, Robert Bosch, Warrendale, PA.

Bowman, J.E. and Law, E.H. (1993) 'A feasibility study of an automobile slip control braking system', *SAE* Paper 930762.

Buckholtz, K.R. (2002a) 'Reference input wheel slip tracking using sliding mode control', *SAE* Paper 2002-01-0301.

Buckholtz, K.R. (2002b) 'Use of fuzzy logic in wheel slip assignment – Part I: yaw rate control', *SAE* Paper 2002-01-1221.

Drakunov, S., Özgüner, Ü., Dix, P. and Ashrafi, B. (1995) 'ABS control using optimum search via sliding modes', *IEEE Transactions Control Systems*, March, Vol. 3, No. 1.

Gordon, T., Howell, M. and Brandao, F. (2003) 'Integrated control methodologies for road vehicles', *Vehicle System Dynamics, International Journal of Vehicle Mechanics and Mobility*, Vol. 40, Nos. 1–3, pp.157–190.

Kazemi, O., Abdollahpour, R., Sedeh, R.S. and Kazemi, H. (2005) 'An adaptive fuzzy controller for anti lock braking system', Paper presented at the *13th International Mechanical Engineering Conference*.

Layne, J.R., Passino, K.M. and Yurkovich, S. (1993) 'Fuzzy learning control for antiskid braking systems', *IEEE Transactions on Control Systems*, Vol. 1, No. 2.

Lee, B.R. and Sin, K.H. (2000) 'Slip-ratio control of abs using sliding mode control', *Science and Technology, KORUS 2000 Proceedings*.

Limpert, R. (1992) *Brake Design and Safety*, SAE Publications, Warrandale, PA.

Madau, D.P., Yuan, F., Davis, L.I. and Feldkamp, L.A. (1993) 'Fuzzy logic anti-lock brake system for a limited range coefficient of friction surface', Paper presented at the *2nd IEEE International Conference on Fuzzy Systems*.

Mauer, G., Gissinger, G. and Chamaillard, Y. (1994) 'Fuzzy logic continuous and quantizing control of an abs braking system', *SAE* Paper 940830.

Mirzaei, M., Moallem, M., Mirzaeian, B. and Fahimi, B. (2005) 'Design of an optimal fuzzy controller for antilock braking systems', Paper presented at *Vehicle Power and Propulsion, IEEE Conference*.

Petersen, I. (2003) 'Wheel slip control in abs brakes using gain scheduled optimal control with constraints', PhD thesis, Dept. of Eng. Cybernetics, Norwegian University of Science and Technology, Trondheim.

Schilke, N.A., Fruechte, R.D., Boustany, N.M., Karmel, A.M., Repa, B.S. and Rillings, J.H. (1989) 'Integrated vehicle control', Paper presented at *Vehicle Technology Conference, 1989 IEEE 39th*, Vol. 2, pp.868–877.

Schürr, H. and Dittner, A. (1984) 'A new anti-skid brake system for disc and drum brakes', *SAE* Paper 840468.

Unlusoy, Y.S., Balkan, T., Tekin, G., Sahin, M. and Oktay, G. (2006) 'Integrated active safety systems for road vehicles', Paper presented at *Traffic and Road Safety International Congress*, Ankara, Vol. 1, pp.479–493.

Watanabe, K., Kobayashi, K. and Cheok, K.C. (1992) 'Absolute speed measurement of automobile from noisy acceleration and erroneous wheel speed information', *SAE* Paper 920644.

Yazicioglu, Y. (1999) 'Development of a fuzzy controlled abs to improve braking performance and stability of automobiles', MS thesis, METU.

Yu, F., Feng, J.Z. and Li, J. (2002) 'A fuzzy logic controller design for vehicle abs with a on-line optimized target wheel slip ratio', *International Journal of Automotive Technology*, Vol. 3, No. 4, pp.165–170.