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# A Comprehensive Model for Adhesion Control System of Wheel and Rail

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**Abstract-** *This paper presents the movement dynamic of the train and the relationship between the speed of wheel and train, as well as a discussion about the concept of wheel slip. There are two different operation regions designated as creep and wheel spin areas for wheel slip. Creep and wheel spin areas have stable and unstable characteristics, respectively. Wheels and rails are constructed from iron, and thus the friction between them is negligible. Therefore, operation point of speed control system may be in either creep or wheel spin areas. The place of the operation point depends on the values of driving torque compared with the value of maximum adhesion torque. As described, in this article too, in order to minimize the acceleration time, the best operation point is maximum adhesion point. To provide a situation to study algorithms of adhesion control, this paper presents a complete model for simulation the adhesion control. Adhesion coefficient is a non-measurable quantity; therefore, an estimator, previously used, for its estimation is used. The traction motor, which is used in this study, is an induction motor. The speed control system of this traction motor is field-oriented control. The presented model is used in operation in creep/wheel spin area and on maximum adhesion point. The simulation results approve the model.*

***Keywords:*** *Ac Drives, Adhesion coefficient, Electrical trains, Traction system, Wheel slip.*

## NOMENCLATURE

| | |
|---|---|
| $\theta$ | Slop angle [rad] |
| $\theta_r$ | Rotor angle [rad] |
| $\lambda$ | Wheel slip |
| $\lambda_m$ | Wheel slip of maximum adhesion coefficient |
| $\mu$ | Adhesion coefficient |
| $\hat{\mu}$ | Estimated adhesion coefficient |
| $\mu_m$ | Maximum adhesion coefficient |
| $\tau_a$ | Adhesion torque |
| $\tau_m$ | Driving torque [N.m] |
| $\omega_{wh}$ | Angular speed of train driven wheel [rad/s] |
| $DTC$ | Direct torque control |
| $F_a$ | Adhesion force [N] |
| $F_m$ | Driving force [N] |
| $F_r$ | Train rolling resistance [N] |
| $FOC$ | Field oriented control |
| $g$ | Gravity of Earth [m/s2] |
| $I.M$ | Induction motor |
| $J$ | Moment of inertia [kg.m2] |
| $k$ | Sampling step |
| $M$ | Mass of train [kg] |
| $N$ | Normal force [N] |
| $r$ | Wheel's radius [m] |
| $s$ | Laplace operator |
| $t$ | Time [sec] |
| $\Delta t$ | Acceleration time [sec] |
| $T_0$ | Time constant of estimator |
| $v_{ref}$ | Train reference speed [m/s or km/h] |
| $v_s$ | Slip speed [m/s] |
| $v_t$ | Train actual speed [m/s] |
| $v_{wh}$ | Speed of train driven wheel [m/s] |

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## 1. INTRODUCTION

A vehicle can travel faster on rail compare to road [1]. One of that reason is; in the railway, all of the rails and wheels of the train are made from iron. These iron surfaces lead to low friction between wheels and rails. This low friction leads to wheel slip. Regarding to adhesion versus wheel slip curve, at a unique value of wheel slip, adhesion coefficient is maximum. Operation on that maximum point will led to minimizing the acceleration time. On the other hand, when the train is in braking mode, by utilizing the maximum adhesion coefficient the braking time will be minimized. In both states of acceleration and braking, the adhesion coefficient can be controlled, by controlling the wheel slip, and utilizing of the maximum adhesion coefficient will be possible. Minimizing the braking time is common between trains, cars, motorcycles, etc.; thus it is reasonable that there are more studies on wheel slip control in braking mode than wheel slip control in acceleration mode. The base of the wheel slip control in braking mode is common between all vehicles. Some researches on wheel slip control in braking mode include Anti-Lock Braking System (ABS) [2,3], estimation of the friction between tire and road [4,5], Brake system with estimation of tire–road friction [6], braking control methods with different driven front and rear wheels [7], adaptive control in the braking time of the train [8] or car [9], and fuzzy logic control for anti-lock braking/traction control systems [10]. There are two models for modeling the wheel slip in the braking mode: Beam and Bristle models. The main application of the Beam model is for car brake and Bristle model's main application is for train brake [11,12]. Studies on acceleration mode are fewer that studies on braking mode. There are many factors affecting the adhesion between wheel and rail e.g. wheel slip, surface conditions of wheel and rail and train speed. Studies on controlling adhesion in acceleration mode mainly deal with control of wheel slip and surface conditions of wheel and rail. Some researches which deal with wheel slip control are include anti-slip re-adhesion control methods [13-15], and sensorless re-adhesion control [16,17]. Some researches which are related to surface conditions of wheel and rail deal with influence of sanding, on the adhesion [18], and control of friction between wheel and rail by on-board lubrication [19]. The other subject which is interesting for researchers in the vehicle speed control field is speed control of traction motors. Motor speed control of electrical tractions consists of AC [20-22] and DC [23] drives. With the development of power electronics utilization of AC motors is preferred. Between AC types of traction motor, the induction one is more popular, because it has a robust and simple construction with little need for maintenance. There are different drives for speed control of AC motors such as scalar control [24, 25], direct torque control [24-26], vector control [24-26], and predictive control [27-31]. By use of the developed multi-level converters [32] the performance of the speed control methods can be improved. Each of these methods has its application, advantages and disadvantages. Another requirement of train speed control systems is adhesion estimator, because adhesion is a non-measurable quantity, which is discussed in [11,33]. All of the above-mentioned valuable studies have been conducted on one aspect of wheel slip control and none of them presents a model for simulation of train speed control. To explore and study train speed control methods in the acceleration time, a model considering the effect of adhesion phenomenon is needed, which is the goal of this paper. Therefore, the main aim of this paper is Providing a model of train speed control equipped with adhesion control.

The rest of this article is organized as follows: section 2 deals with a brief discussion of adhesion coefficient and wheel slip. In section 3, equations of train motion are discussed. In section 4, a previously used estimator for adhesion coefficient is reviewed. In section 5, a model for speed control of traction motor is presented. Speed control of train with/without adhesion control and their simulation results are presented in section 6. Section 7 is dedicated to the paper conclusion.

## 2. CONCEPTS OF ADHESION COEFFICIENT AND WHEEL SLIP

Before discussion of adhesion control system and wheel slip, the phenomena of adhesion coefficient and wheel slip should be explained. The difference between speed of the train (the linear speed of the train, as shown in Fig. 1 and linear speed of the train's driven wheel is defined as the slip speed, meaning that [1,7,23,33]:

$$v_s = v_{wh} - v_t \tag{1}$$

The linear speed of the train driven wheel can be obtained by multiplying the driven wheel's angular velocity ($\omega_{wh}$) by driven wheel's radius *(r)*, [1,7,23,33], like Eq. (2):

$$v_{wh} = r.\omega_{wh} \tag{2}$$

The slip ($\lambda$) is a dimensionless quantity, which can be calculated as follows [1,7,23,34]:

$$\lambda = \frac{v_s}{v_t} = \frac{v_{wh} - v_t}{v_t} \tag{3}$$

Then, adhesion coefficient ($\mu$) can be defined as surface adhesion coefficient between the train's wheel and rail in contact place. The main reason of train movement is the friction between train's wheel and rail. When the traction motor tries to push forward the train, by increasing the driving torque, the driven wheel begin to rotate. Since there is friction between wheel and rail (adhesion) the driving force will be applied to tracks and pushes the train forward. It must be considered that for occurrence adhesion, a non-zero wheel slip is necessary. In the other word as shown in Fig. 2, for a zero wheel slip, the adhesion coefficient is around zero. By increasing the driving torque in order to accelerate the train, wheel slip will be increased. Increasing the wheel slip up to a unique value (i.e. wheel slip corresponding to maximum adhesion coefficient ($\lambda_m$)), leads to enhancing the adhesion coefficient. The result of increasing the wheel slip more than that unique value ($\lambda_m$) is decreasing the adhesion coefficient, which leads to operation in wheel spin area.

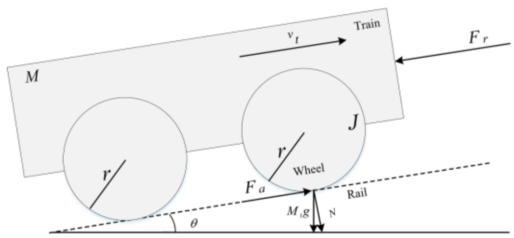


**Fig. 1. Simple model of train motion**

Since wheel spin will cause depreciation in wheels and cause problems in speed control system, working in the wheel spin area is not desirable. It can be said that, operation in the creep area is relatively better than operation in the wheel spin area, and the best choice is operating on $\lambda_m$ point. But $\lambda_m$ is not a certain constant point, and several factors affect it and value of adhesion coefficient ($\mu$). Main of that factors can be summarized as wheel and rail's surface conditions, and speed of the train [19, 35, 36]. The condition of wheel and rail contact place is the most important parameter of limiting maximum adhesion value ($\mu_m$) and its wheel slip ($\lambda_m$). When the contact surface of wheel and rail is dry and clean, the adhesion between wheel and rail will be maximized and its wheel slip ($\lambda_m$) has its minimum value. When there are moisture, oil and leaves on the tracks the maximum adhesion coefficient ($\mu_m$) has its minimum value while its wheel slip ($\lambda_m$) has its maximum value, which is the worst situation for acceleration as well as for wheel and tacks lifetime. In addition to the contact surface condition, adhesion coefficient also depends on the speed of train. Maximum of the adhesion coefficient will be decreased by increasing the speed of train, which means the adhesion coefficient and speed of train have an inverse relationship. Some papers and books use adhesion versus slip speed curve ($\mu$-$v_s$ curve) instead of adhesion versus wheel slip curve ($\mu$-$\lambda$ curve). Basically there is no difference between applications of these curves, because none of them are fixed and as mentioned, some factors such as train speed, condition of rail and wheels, etc., affect these curves.

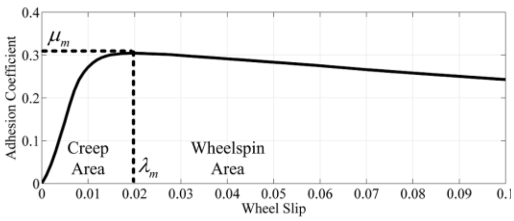


**Fig. 2. Adhesion versus wheel slip curve [35]**

## 3. MOTION EQUATIONS OF MOVING OBJECT AND MODELING

In order to simulate train speed control system with adhesion control, it is necessary to review motion equation of the train by considering the wheel slip and the adhesion behavior. For this purpose, assume a simple model of a moving object, as a locomotive, like Fig. 1. When the driving torque applies to the wheel, the adhesion force will push the train forward, but the rolling resistance is in the opposite direction of this force. The simulated train's rolling resistance is shown in Fig. 3 [37]. The assumed locomotive has Four traction motors, so ¼ of the train's rolling resistance (i.e., ¼ of the Fig. 3, rolling resistance) should be considered in the simulation. As discussed, for the occurrence of adhesion, a non-zero wheel slip is needed. So when the train is on acceleration mode the linear speed of the driven wheel is greater than train speed. Eqs. (1) - (3) along Eqs. (4) - (9) can show the behavior of a moving object such as the locomotive. Simultaneous solution of these equations is necessary for the modeling of train movement with wheel slip [1, 23, 34, 38]:

$$M\frac{d}{dt}v_t = F_a - F_r - MgSin\theta \tag{4}$$

$$F_r = k_0 + k_1 \cdot V_t + k_2 \cdot V_t^2 \tag{5}$$

$$F_a = \mu(\lambda).N \tag{6}$$

$$J\frac{d}{dt}\omega_{wh} = \tau_m - \tau_a \tag{7}$$

$$\tau_a = F_a.r \tag{8}$$

$$\tau_m = F_m.r \tag{9}$$

To obtain a train movement model it is clear that Eqs. (1) - (9), should be solved simultaneously.

## 4. ADHESION ESTIMATION

Since the adhesion coefficient is not an output of any equation, an estimator is needed for its estimation. For this purpose, the estimation method which has been used in [11] is used and its performance is as follow:

From Eqs. (6) - (8) is cleared that:

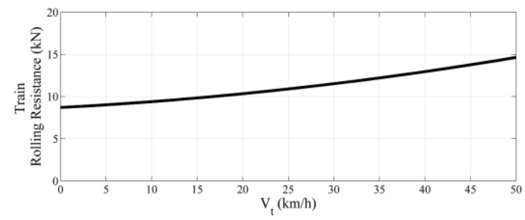


**Fig. 3. Train rolling resistance**

$$J\frac{d}{dt}\omega_{wh} = \tau_m - N \cdot \mu(\lambda) \cdot r \tag{10}$$

Thus, it is expected that Eq. (11) can estimate the adhesion coefficient.

$$\mu(\lambda) = \frac{(\tau_m - s\,\omega_{wh})}{(N \cdot r)} \tag{11}$$

But it is should be consider that in estimation equations derivative operator can be replaced. Hence derivative operator (i.e. Laplace operator (s)) could be replaced by Eq. (12):

$$s = \frac{1}{T_0}\left(1 - \frac{1}{1+sT_0}\right) \tag{12}$$

So the adhesion coefficient can be estimated by Eq. (13) (inferred and obtained from [11]):

$$\hat{\mu}(\lambda) = \frac{\left(\tau_m - \frac{1}{T_0}\left(1 - \frac{1}{1+sT_0}\right)J \cdot \omega_{wh}\right)}{(N \cdot r)} \tag{13}$$

By Eqs. (1) - (13) model of train's movement is ready. By combining adhesion estimator with Fig. 4, the train movement model equipped with adhesion estimator will be obtained. The performance of the estimator is validated for rapid change of adhesion coefficient, which is shown in Fig. 4.

## 5. BASE OF TRACTION MOTOR SPEED CONTROL

The main part of any vehicle is its propulsion motor. There are several types of electrical motors for propulsion applications. Induction motors are widely used in traction systems, because of their simple structures, fine performance and easy maintenance. Therefore, in this article, an induction motor is selected for traction motor part.

For speed control of induction motors there are a variety of methods such as scalar control, field oriented control (FOC), direct torque control (DTC), predictive control, etc.

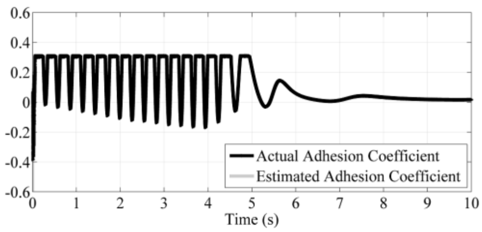


**Fig. 4. Actual adhesion coefficient and estimated adhesion coefficient**

These methods are discussed in [24,25,39-41]. For speed control of induction motors in industry applications, DTC and FOC are preferred. In the train traction motor, the dynamic of the control system should be controlled. Therefore, FOC is selected for speed control of traction motor (i.e. induction motor). One of the widely used scheme of FOC, for induction motor, is used in this paper, which is shown in Fig. 5 (FOC schemes with different appearances are illustrated in [25,42-44]).

## 6. SPEED CONTROL OF TRACTION MOTOR WITHOUT/WITH ADHESION CONTROL

Now, by combining the train movement model, adhesion estimator and field-oriented control of induction motor, a model of train speed control with adhesion control can be achieved Like Fig. 5. The set point of the control system is train reference speed. To highlight the advantage of using adhesion control in train speed control, both states of train speed control with and without adhesion control are simulated. In all simulations of this paper, the reference speed is 1m/s and this reference is applied to the speed control systems in $t$ = 4 s.

### 6.1 Train speed control without adhesion control

By referring to Fig. 2, which presents the adhesion coefficient versus wheel slip, it can be seen that, the best wheel slip for use of maximum adhesion is λm point. But with regard to Section 2 (impacts of the rail surface condition and train speed on the adhesion versus slip curve), wheel slip of the maximum adhesion is not a certain constant point. If the speed control does not have an adhesion control in acceleration time, the operation point maybe in either creep or wheel spin areas, or in both of these two areas.

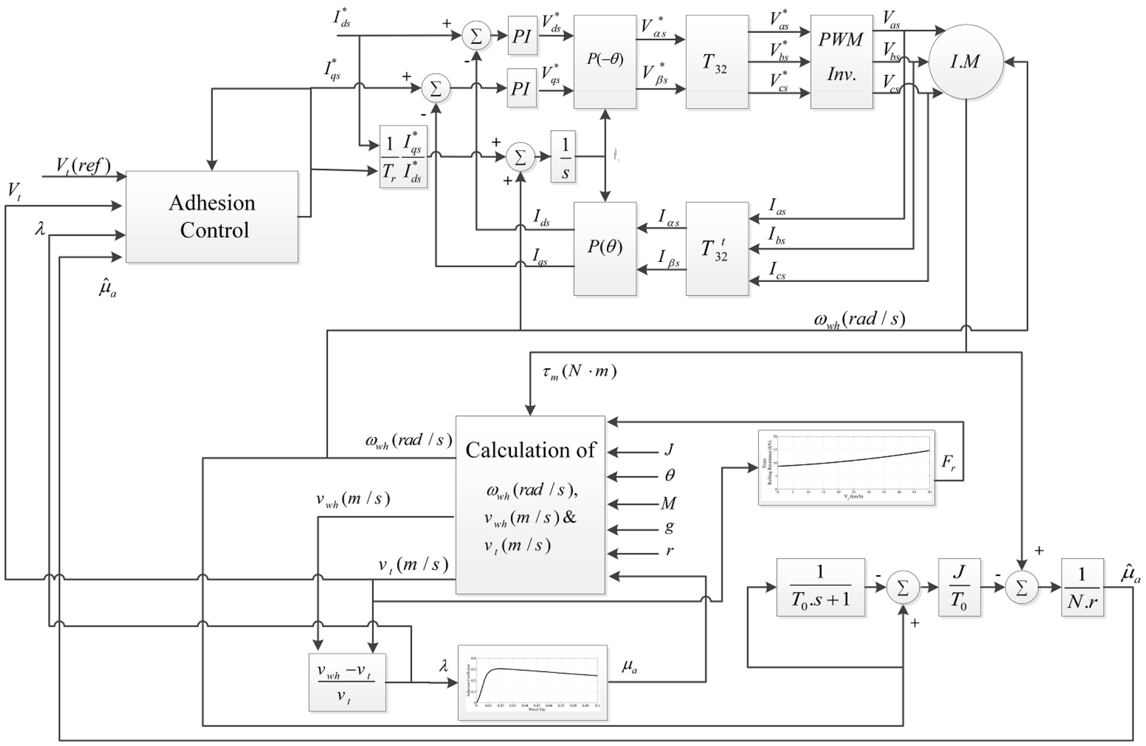


**Fig. 5. Block diagram of train speed control equipped with adhesion control**

When the applied driving torque is less than the maximum adhesion torque, the operation point will be in creep area. On the other hand, when the applied driving torque is greater than the maximum adhesion torque, the operation point will be in the wheel spin area.

**6.1.1. Operation in Creep Area**

In order to ensure that, in the acceleration time, the operation point is not transferred to the wheel spin area the operation point should be limited in the creep area. Therefore driving torque must be limited. By applying this control method, simulation results are illustrated in Figs. 6 and 7. (The reference of the speed control system is applied in t = 4 s).

As shown in Figs. 6 and 7, after applying the speed control in t = 4 s, it takes about t = 4.3 s for the train to reach its reference speed (i.e., t = 8.3 s). Regarding Figs. 2 and 7, in all of the acceleration time, operation point is in creep area because the wheel slip is less than the wheel slip of the maximum adhesion coefficient.

**6.1.2. Operation in Wheel spin Area**

The acceleration time has a reverse relationship with the adhesion coefficient. Thus to reduce the acceleration time, the adhesion coefficient should be enhanced. Consequently, the limiter of the driving torque is omitted and motor speed limiter has been added. But as illustrated in Fig. 8 and 9 by using this method the operation point is transferred to the wheel spin area.

By regard to Figs. 8 and 9 rising time by operation in the wheel spin area is less than operation in the creep area ($\Delta t$ = 4 s, compared to $\Delta t$ = 4.3 s). However, the wheel slip in this method is extremely large (the speed limiter, limits wheel slip up to 2). This high value of wheel slip will led to deprecation of wheel. Therefore, none of these two operation area have an optimum acceleration situation. Therefore, another point between these two areas can be desirable. Since λm has the maximum adhesion coefficient, operation on this point will lead to minimizing of acceleration time. In other words operation point must be at (λm,μm).

## 6.2. Train speed control with adhesion control

Now assume that the wheel slip of the maximum adhesion has a certain value. The target of the train speed control system, equipped with the adhesion control is utilizing maximum adhesion, in all of acceleration time. Regarding to Fig. 2 maximum adhesion point is on, λm = 0.02 and μm = 3.1. With a control system, which operates on λm, compared to train speed controls without adhesion control, reduction of acceleration time is expected. Which the simulation results, as shown in Figs 10 and 11, approve this idea. Like previous sections, the reference of the control system is applied at t = 4 s.

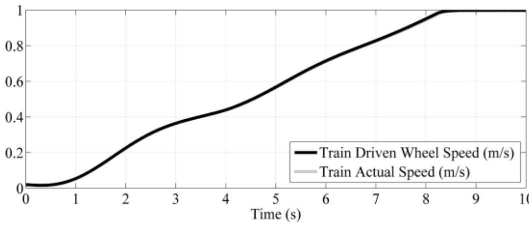


**Fig. 6. Train driven wheel operation point is in creep area speed (m/s) and actual speed of train (m/s), without adhesion control when**

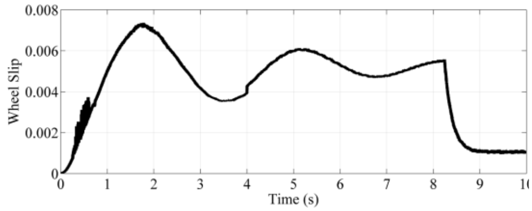


**Fig. 7. Wheel slip of train, without adhesion control when operation point is in creep area**

As shown in Fig 11 in all of the acceleration time the wheel slip is around 0.02. Fig. 2, shows that λm = 0.02. Therefore it can be said that in the acceleration time, the adhesion coefficient is near its peak. Referring to Fig. 10, acceleration time is about 2.2 s ($\Delta$t = 6.2 s - 4 s).

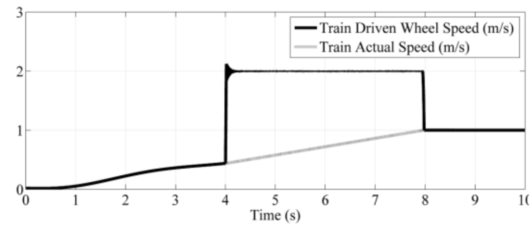


**Fig. 8. Train driven wheel speed (m/s) and actual speed of train (m/s), without adhesion control when operation point is in wheelspin area**

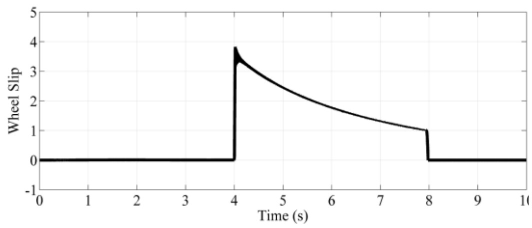


**Fig. 9. Wheel slip of train, without adhesion control when operation point is in wheelspin area**

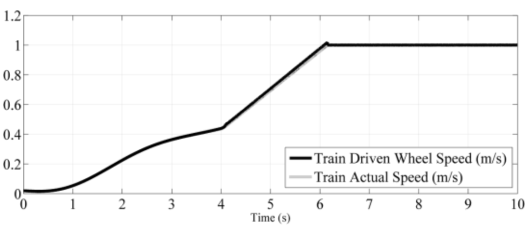


**Fig. 10. Train driven wheel speed (m/s) and actual speed of train (m/s), with adhesion control when operation point is on maximum adhesion coefficient**

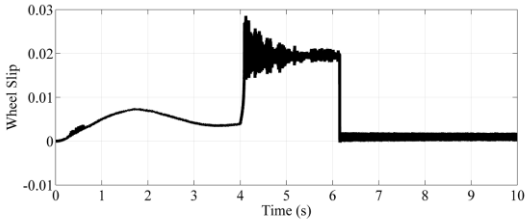


**Fig. 11. Wheel slip of train, with adhesion control when operation point is on maximum adhesion coefficient**

By comparing Figs. 6 and 8, and 10, it becomes obvious that the minimum of the acceleration time belongs to the adhesion control system. Acceleration time in the mode of "without adhesion control when operation point is in wheel spin area" is less than acceleration time in the mode of "without adhesion control when operation point is in creep area" but refer to Fig. 8 and 9, the depreciation of rail and wheel in that situation is very high. So operation in wheel spin area cannot be desirable. Therefore optimum operation point for minimizing acceleration time and optimizing depreciation of wheel is on the maximum adhesion point.

## 5. CONCLUSIONS

As explained also in this paper, acceleration time is a function of adhesion coefficient. Because of low negative slope of adhesion versus wheel slip curve in the wheel spin area compared to sharp positive slope of adhesion versus wheel slip curve in the creep area, generally can be said operation in wheel spin area has less acceleration time compared to creep area. In the other hand, operation in the wheel spin area will lead to high deprecation. As has been shown, the best operation point is on the maximum adhesion point. In this situation, the train acceleration is maximum and wheel and rail deprecation is optimum. Therefore, in speed control of train the impact of adhesion on acceleration must be considered. Hence this paper presents a speed control model of train obtained from combining field oriented control of induction motor (induction motor as traction motor), adhesion part and adhesion coefficient estimator. The operation point maybe either in creep/wheel spin area or on maximum adhesion point. All of these situations are simulated and tested in this paper, by the presented model.

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