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The test of electric vehicle with electronic differential system in different road conditions

Elektronik diferansiyel sistemli elektrikli aracın farklı yol koşullarında testi

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The Test of Electric Vehicle with Electronic Differential System in Different Road Conditions

Highlights

- *An electric vehicle prototype, driven by an electronic differential system, was built.*
- *The simulation of the mathematical model of the electronic differential system has been introduced to the literature.*
- *The electronic differential system was tested and validated under different road conditions.*

Graphical Abstract

The basic electric vehicle structure in the figure is ensured that mechanical parts such as gearbox, cardan shaft and differential box are not used on the vehicle. For this reason, it causes a decrease in vehicle weight, which is an important parameter for the range of electric vehicle.

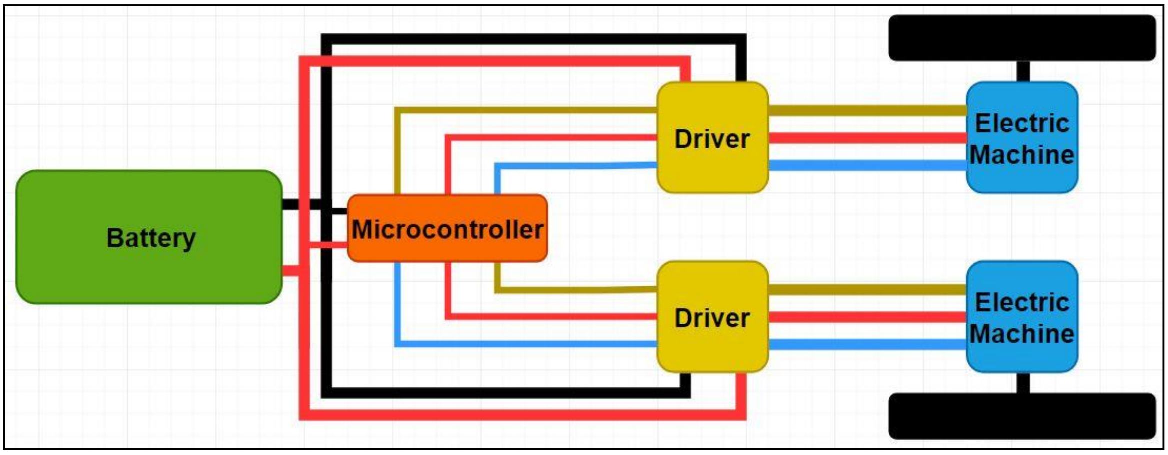

Figure. Basic structure of the electric vehicle using electronic differential system

Aim

Presented other studies in the literature is usually tested the electronic differential system in the simulation platform such as MATLAB/SIMULINK. The aim of this study is to test the electronic differential system under different road conditions besides the presented simulation in the literature.

Design & Methodology

A two-wheel drive electric vehicle was designed and an electronic differential system created using the Ackermann-Jeantand theorem was applied to this vehicle.

Originality

In addition to the electronic differential system studies in the literature, the system has been tested under three different road conditions and the results are given in the article.

Findings

It has been observed that there is no obstacle in the application of the electronic differential system to an electric vehicle. In addition, since the system is electronic, it has become easier to apply algorithms to increase the vehicle's cornering ability.

The performance of the created EDS has been investigated. It has been observed that the vehicle can maintain its balance while cornering and moving in three different road conditions.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission

The Test of Electric Vehicle with Electronic Differential System in Different Road Conditions

Research Article

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ABSTRACT

The harmful gases emitted by vehicles using oil-based fuels have been widely discussed in recent years. For this reason, in vehicle technology, a tendency has started to use vehicles with lower greenhouse gas effect engine types. Electric motor vehicles are more complex in terms of control when compared to internal combustion engine vehicles. However, it offers a much more comfortable use for essential needs such as cleaning, maintenance and repair. There are many studies in the literature on mathematical simulations of electronic differential system (EDS) and laboratory scale EDS trials for electric vehicles. In this study, the mathematical model of EDS for an electric vehicle, is simulated. Unlike previous studies, the mathematical model of EDS was embedded on a microprocessor and used to control a prototype electric vehicle. Real road tests were carried out with the prototype electric vehicle. Simulation and road tests were carried out under 3 different road conditions (dry, wet and slippery) and 3 different steering angles (5^o, 15^o, ve 25^o). In order to interpret the results, current and speed data of the right and left wheels on the prototype vehicle were taken in real time. The results confirm that the vehicle does not spin when turning in different road conditions.

Keywords: Electronic differential system, simulation, validation, electric vehicle.

Elektronik Diferansiyel Sistemli Elektrikli Aracın Farklı Yol Koşullarında Testi

ÖZ

Petrol kaynaklı yakıt kullanan araçların doğaya saldıkları zararlı gazlar son yıllarda oldukça gündeme gelmiştir. Bu nedenle taşıt teknolojisinde sera gazı etkisi daha düşük olan motor tiplerinin kullanılacağı araçlara yönelim başlamıştır. Elektrik motorlu araçlar, içten yanmalı motorlu araçlarla kıyaslandığında kontrol açısından daha kompleks yapıda olsalar da temizlik, bakım ve onarım gibi başlıca ihtiyaçlarda çok daha rahat bir kullanım sunmaktadırlar.Literatürde elektrikli taşıtlar için elektronik diferansiyel sistemi (EDS) matematiksel simülasyonları ve laboratuvar ölçekli EDS denemeleri üzerine birçok çalışma bulunmaktadır. Bu çalışmada elektrikli bir taşıt için matematik modeli oluşturulan EDS 'nin simülasyonu yapılmıştır. Önceki çalışmalardan farklı olarak EDS için kullanılan matematik model bir mikroişlemci üzerine gömülerek prototip bir elektrikli taşıtın kontrolü için kullanılmıştır. Prototip elektrikli araç ile gerçek yol testleri gerçekleştirilmiştir. Simülasyon ve yol testleri 3 farklı yol şartında (kuru, ıslak ve kaygan) ve 3 farklı direksiyon açısında (, , ve) gerçekleştirilmiştir. Sonuçların yorumlanabilmesi için prototip araç üzerindeki sağ ve sol tekerleklerden akım ve hız bilgisi anlık olarak alınmıştır. Sonuçlar aracın farklı yol şartlarında dönerken kaymadığını doğrulamaktadır.

Anahtar Kelimeler: Elektronik diferansiyel sistemi, simülasyon, validasyon, elektrikli taşıt.

1. INTRODUCTION

The use of fossil fuels has increased dramatically, As a result of the global industry development in the 19th and 20th centuries. Therefore, the occurring emissions have created a greenhouse gas effect on the atmosphere. In addition, the widespread use of fossil-sourced fuels has caused an increase in air pollution in cities, thus negatively affecting public health. For such reasons, researchers have done many studies to solve the emission problem of fossil fuels. One of these approaches is to use electric motors instead of internal combustion engines in transportation vehicles [1, 2]. A vehicle using an internal combustion engine can be converted into an electric vehicle in several ways. An electric vehicle (EV) can be created by removing the internal combustion engine on a vehicle and replacing it with an electric motor that will perform the same function [3]. In addition, an electric vehicle can be obtained by removing the power transmission systems with the drive system, by connecting electric motors to the rear two wheels for drive. This approach is schematically given in Figure 1 [4].

The approach, whose schematic is given in Figure 1, causes more difficult algorithms in terms of control than single-engine electric vehicles. Despite this, the vehicle does not need mechanical parts such as gearbox, cardan shaft and differential box that have a high weight on the vehicle. This approach will enable the electric

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vehicle to be lighter in terms of vehicle weight and also allow it to travel longer distances with the same battery. In this system, the tasks of the removed mechanical parts are determined and these tasks are done by the motors in the rear two wheels with EDS [4].

transmission topologies of electric vehicles using fuzzy logic in Simulink. It has been observed that a strong control and energy performance optimization is provided thanks to the fuzzy logic algorithm [11].

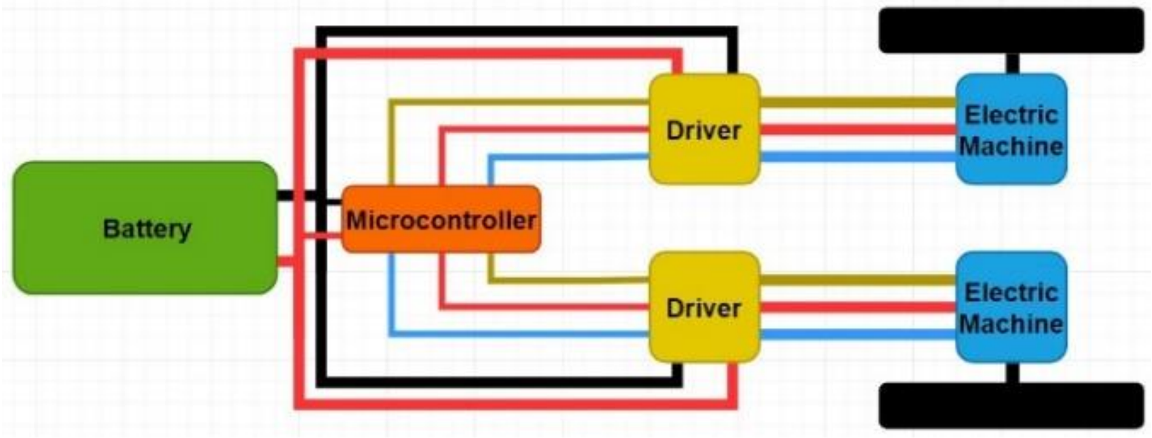


Figure 1. Fundamental structure of electric vehicle using electronic differential system

When a vehicle moves along a winding road lane, the speed of the inner wheel must be different from the speed of the outer wheel in order to turn stably it. Because each wheel of an electric vehicle driven a direct wheel has an independent driving force, an electrical differential system is required. Hartani et al. In his study, he simulated the rotational performance of an electric vehicle driven by a rear two-wheel electric motor. The mathematical model of the electronic differential in simulation has been obtained by utilizing the Ackermann - Jeantand Theorem (AJT). The simulation results show that the EDS model created for the electric vehicle has a good dynamic performance [5]. Hartani et al. In a different study, he made direct torque control with fuzzy logic controller for each wheel motor. Good vehicle stability was observed on a curved road as a result of various simulation scenarios [6]. In another study, Haddoun et al. developed a single chip that contained control of both electronic differential and asynchronous motors. Using the NEDC (the New European Driving Cycle) test cycle, a prototype study was carried out in a laboratory with two 0.9kW induction motors in the powertrain [7]. Yıldırım et al. simulated their EDS model in Matlab / Simulink. They tested the simulation results with a laboratory scale experimental setup using the Codesys utility. As a result of the study by changing the wheel angle from 1^o to 15^o, it was seen that the results of the simulink model and the Codesys program were appropriate [8]. Castro et al. set up an experimental setup in the laboratory where they use EDS with induction motors. It has been observed that this approach is suitable for EDS control by experimentally controlling induction motors with an FPGA (Field Programmable Gate Array) based control [9]. Hua et al. Unlike other studies, the yaw that occurs in the bend was controlled with EDS and fuzzy logic [10]. Popov et al. In their study, they performed EDS control for 3 different power

There are many studies in the literature on mathematical simulation and laboratory-scale trials on EDS for electric vehicles. In this study, the mathematical model of EDS for an electric vehicle is simulated. The functions of the mechanical differential system are completely determined, modeled and electric motors on electric vehicle is operated as removed mechanical differential system. In other words, AJT is expressed in software. Unlike most previous studies, the mathematical model of EDS was embedded on a microprocessor and used to control a prototype electric vehicle. Real road tests were carried out with the prototype electric vehicle. Simulation and road tests were carried out under 3 different road conditions (dry, wet and slippery) and 3 different steering angles (5^o, 15^o, ve 25^o). In order to interpret the results, current and speed data of the right and left wheels on the prototype vehicle were taken in real time. The results confirm that the vehicle does not lose its dynamic stabilization when turning in different road conditions.

2. MECHANICAL STRUCTURE OF ELECTRIC VEHICLE

For use in laboratory research, a prototype electric vehicle has been built. Dimension parameters of the electric vehicle are length 800 mm, width 600 mm and wheel diameter 390 mm.

Two DC motors with reducers were used on the vehicle for driving. In the study, current and speed data are collected from the electric motors on the vehicle. The physical design of the vehicle is shown in figure 2.

The parameters of the motor used on the vehicle are voltage 24 V DC, No-load Speed 4200RPM, Power 420-Watt, Reduction Ratio 1/10.

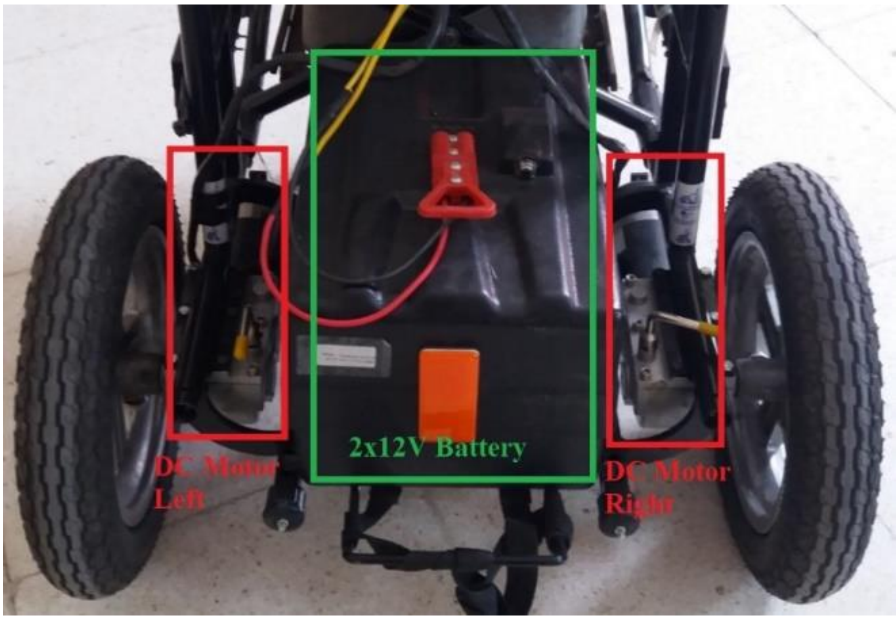


Figure 2. The drive systems in the designed vehicle

The parameters of the motor used on the vehicle are voltage 24 V DC, No-load Speed 4200RPM, Power 420-Watt, Reduction Ratio 1/10.

3. THE SIMULATION OF ELECTRONIC DIFFERENTIAL SYSTEM

One of the two main tasks of the differential system is to turn the power generated by the engine 90 degrees and transfer it to the right and left wheels. Another task is to make the wheels rotate at different speeds depending on the turning radius. When using EDS, there is no need to turn the power produced by the engine 90 degrees, which is one of the main tasks. The reason for this is that DC motors that will drive both wheels without the drivetrain are directly connected. For the second basic task, since the distance of the inner wheels during the rotation is less than the outer wheels, the inner wheels have to turn slower. The AJT model given in Figure 3 is used to solve this problem.

The angles of the inner and outer wheels according to the direction of rotation were calculated using the AJT model given in Figure 3. The main variables are *l* wheelbase(m), *k* king-pim distance(m) and d steering angle.

$$R_{rear-in} = \frac{l}{\tan(d)} - \frac{T}{2} \tag{1}$$

$$R_{rear-out} = \frac{l}{\tan(d)} + \frac{T}{2} \tag{2}$$

$$R_v = \sqrt{\left(R_{rear-in} + \frac{T}{2}\right)^2 + {l_g}^2} \tag{3}$$

In the eq.(1), eq.(2) and eq.(3); $R_{rear-in}$ (m) is distance of rear inner wheel to center of rotation, $R_{rear-out}$ (m) is distance of rear outer wheel to center of rotation, T (m) is axle distance of electric vehicle.

Angular speeds of rear wheels;

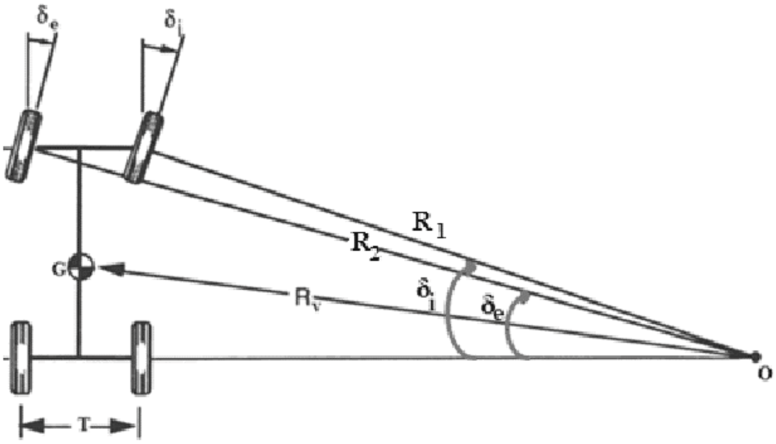


Figure 3. The model of Ackermann-Jeantand Theorem [12].

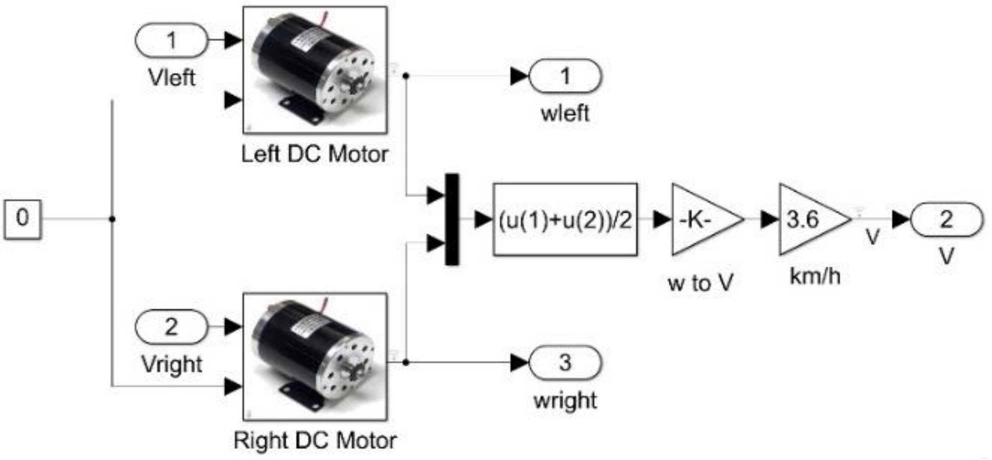


Figure 5. The model of vehicle with EDS

$$\omega_{rear-in} = \frac{v.R_{rear-in}}{R_v.r} \quad (4)$$

$$\omega_{rear-out} = \frac{v.R_{rear-out}}{R_v.r} \quad (5)$$

In the eq.(4) and eq.(5); R_v (m) is distance of electric vehicle gravity center to center of rotation, $w_{rear-in}$ (rad/sec) is angular speed of the rear inner wheel, $w_{rear-out}$ (rad/sec) is angular speed of the rear outer wheel, r (m) is rear-wheel radius of electric vehicle, v (m/sec) is speed of electric vehicle and l_g (m) is perpendicular distance of vehicle gravity center to axle distance.

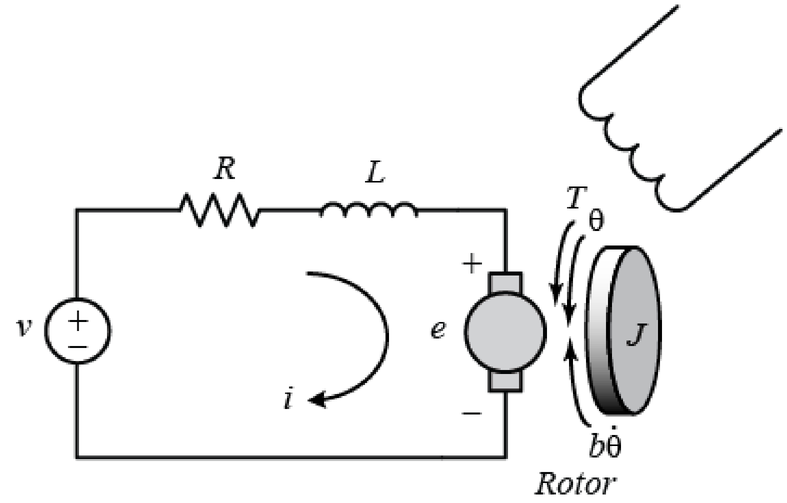


Figure 4. The equivalent circuit of DC motor [13].

Table 1. The parameters of prototype electric vehicle

l (Wheelbase)	0.740 m
k (king-pim distance)	0.4 m
T (axle distance)	0.65 m
r (wheel radius)	0.195 m

The above parameters were taken directly from the prototype electric vehicle. The l_g length is taken as half of the wheelbase.

The systems are divided into subsystems in order to simulate the electric vehicle with the data obtained. Sub-systems in electric vehicles are considered as electronic differential system and modeling of electric motors.

The equivalent circuit of the DC motor used on the vehicle is given in figure 4. In order to model the electrical circuit given in Figure 4, input and output parameters must be determined. Voltage and angular velocity are considered as input and output respectively for DC motor. Thus, when the necessary mathematical operations are calculated, the transfer function of the electric motor is obtained as given in the eq.(6).

$$\frac{\dot{\theta}(s)}{V(s)} = \frac{K}{(Ls+R)(Js+b)+K^2} \quad (6)$$

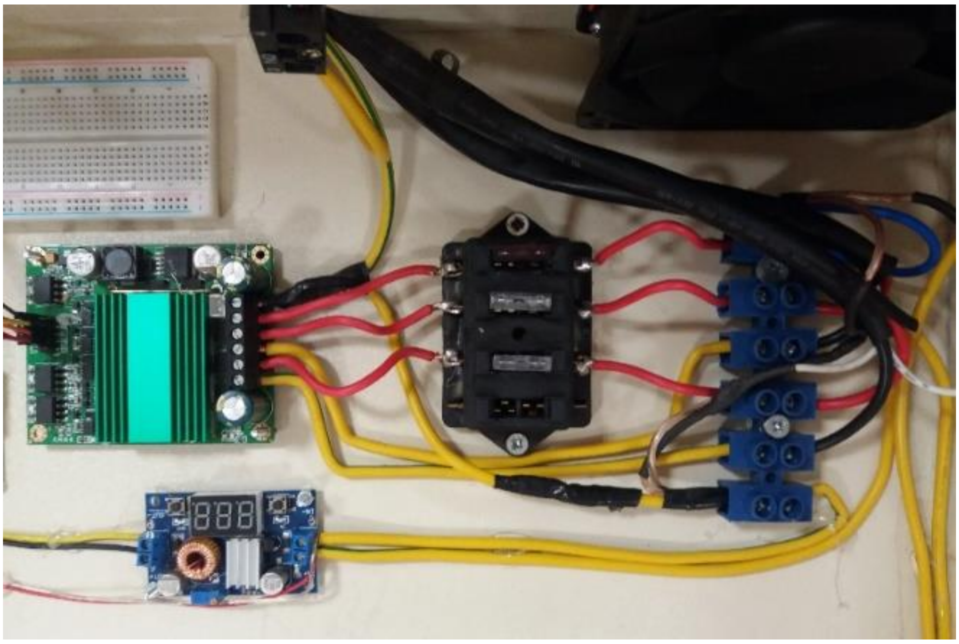


Figure 6. The basic structure of the control system

In order to realize the rotation function of the vehicle, the DC motor model created with eq.(6) is combined with the AJT model. As a result, the vehicle model given in Figure 5 was created in MATLAB / Simulink.

The reference angular velocities of the right and left wheels are obtained from the electronic differential. A stable rotation process is performed by suppling the voltage required for these angular velocities to the motors.

4. THE APPLICATION OF ELECTRIC VEHICLE

The mathematical model of EDS is embedded in a microprocessor. The microprocessor generates PWM signals for electric motors connected to wheels based on the data obtained from the mathematical model. In line with this process, the wheels are turned at their reference speed thanks to the signals generated by the microprocessor. System software is embedded on the STM32F103 microprocessor developed by STMicroelectronics. System Workbench for STM32 software, based on Eclipse, was used as the code compilation and loading program. Thus, the wheels turn at the desired value. The control system is shown in Figure 6.

Wheel angle in vehicles is known to be in the range of [-30^o, + 30^o] [14]. The electric vehicle prototype was tested on three road conditions with different friction coefficients and circular road trajectory with 5^o, 15^o and 25^o steering angles and the results were observed. Approximate friction coefficients of test areas are given in Table 1. Steering angle is taken from the control by telemetry. This data is given as input data to the mathematical model and reference speed values are obtained. According to these speed values, the system is controlled by ARM processor. The electric vehicle was controlled according to the desired steering angle and speed value.

Table 2. Approximate friction coefficients of test areas [14]

Test area	Approximate friction coefficients
Dry	0.90 - 1.05
Wet	0.75 - 0.85
Slippery	0.55 - 0.70

5. RESULTS AND DISCUSSIONS

The speed data of the wheels obtained as a result of the road tests carried out are given in Figures 6, 7 and 8

Table 4. Slip values according to the steering angle for slippery test area

	Left wheel	Right wheel
5^o	%1.46	%1.46
15^o	%1.70	%1.70
25^o	%3.40	%3.40
Average	%2.19	%2.19
Difference	%0.00	

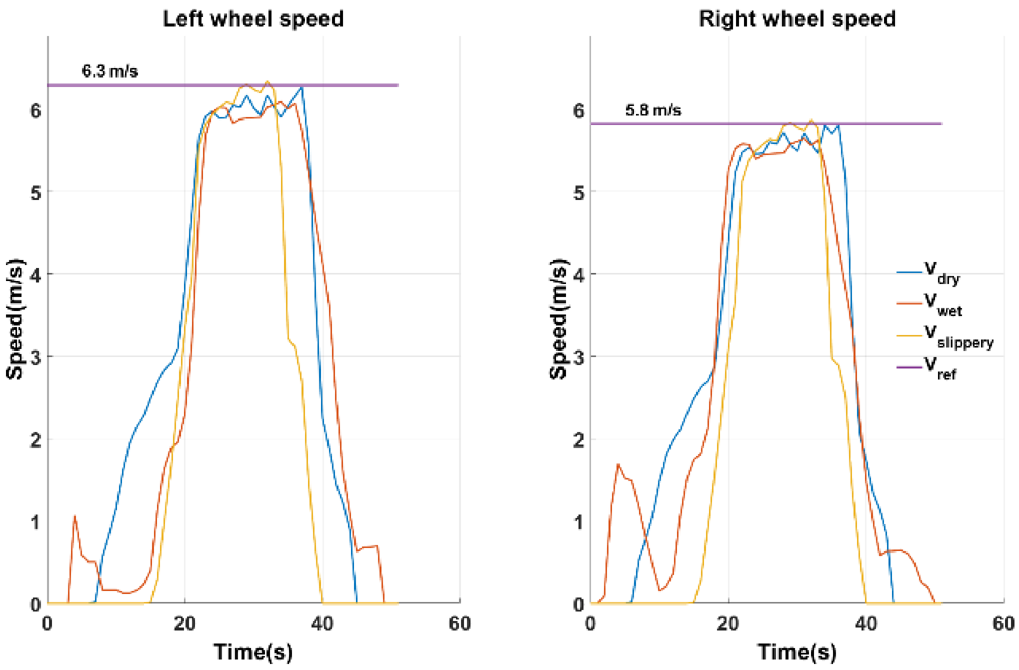


Figure 6. The wheel speed data on three different test areas at 5° right turn of the electric vehicle

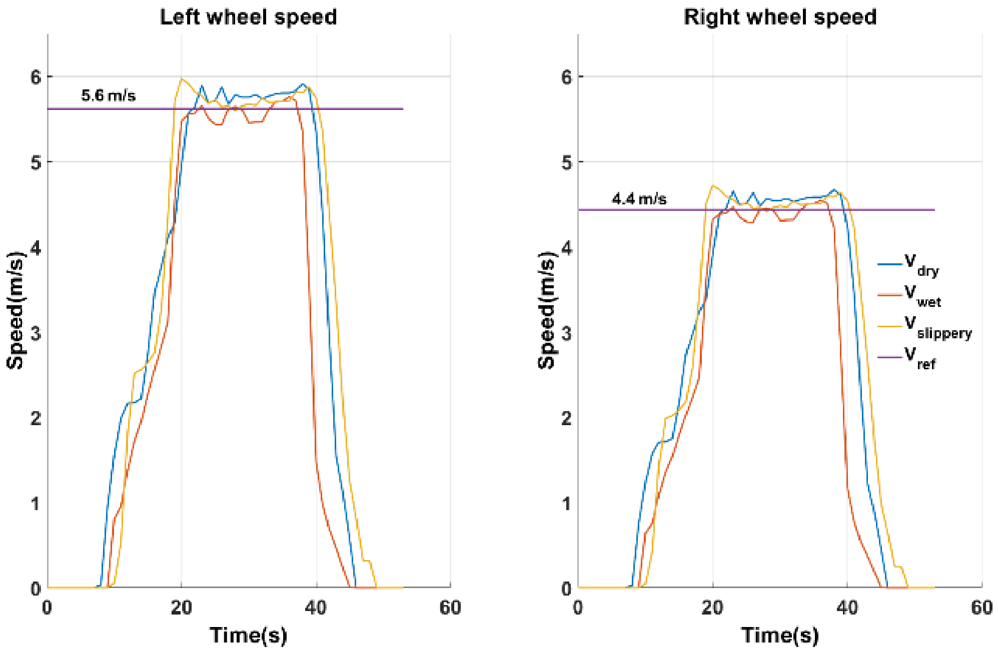
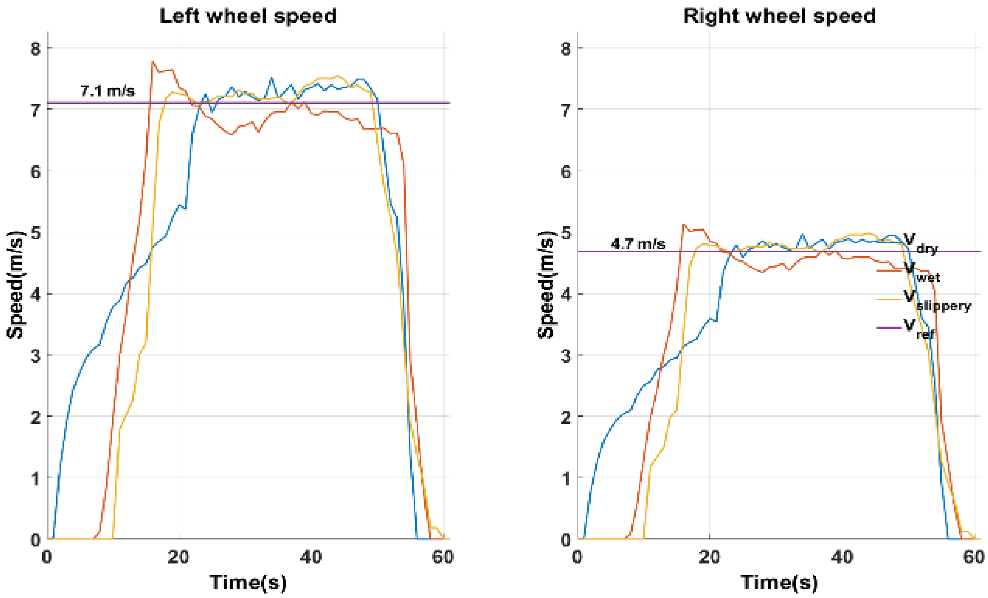


Figure 7. The wheel speed data on three different test areas at 15° right turn of the electric vehicle


Left wheel speed

Right wheel speed

Figure 8. The wheel speed data on three different test areas at 25° right turn of the electric vehicle

When the graphics were examined independently from the steering angle, the EDS control was ensured the control of system in all road conditions. As well as, it is experimentally observed that as the steering angle increases, the difference in speed between the right and left wheels increases.

$$s = \frac{|v_{AJT} - v_{real}|}{v_{AJT}} \qquad (7)$$

In eq.(7), the mathematical expression of the slip in wheel speed for vehicles is given. This expression is one of the most important parameters that express whether the speed of vehicle catches to the reference speed or not [14]. In line with the tests performed with the EDS control, the average slip value was calculated for three different test aeras and three different steering angles by using eq.(7). Afterwards, the average slip value for each test area was obtained by averaging the data on the same test area but at different steering angles. As a result, the slip values according to the state of test area and steering angles are given in tables 2, 3 and 4.

Table 2. Slip values according to the steering angle for dry test area

	Left wheel	Right wheel
5°	%3.32	%3.32
15°	%2.43	%2.66
25°	%2.13	%2.13
Average	%2.63	%2.70
Difference	%0.07	

Table 3. Slip values according to the steering angle for wet test area

	Left wheel	Right wheel
5°	%2.85	%2.85
15°	%2.50	%2.50
25°	%1.88	%1.88
Average	%2.41	%2.41
Difference	%0.00	

Table 4. Slip values according to the steering angle for slippery test area

	Left wheel	Right wheel
5º	%1.46	%1.46
15º	%1.70	%1.70
25º	%3.40	%3.40
Average	%2.19	%2.19
Difference	%0.00	

When the slip data given in Tables 2, 3 and 4 are examined, it is seen that the EDS control used is effective in all road conditions considered in experimental studies. Therefore, the designed electric vehicle was able to turn the bends stably. The current data of DC motors driven the wheels were continuously measured and recorded during experimental studies. Electric motor current data are given in figures 9, 10 and 11

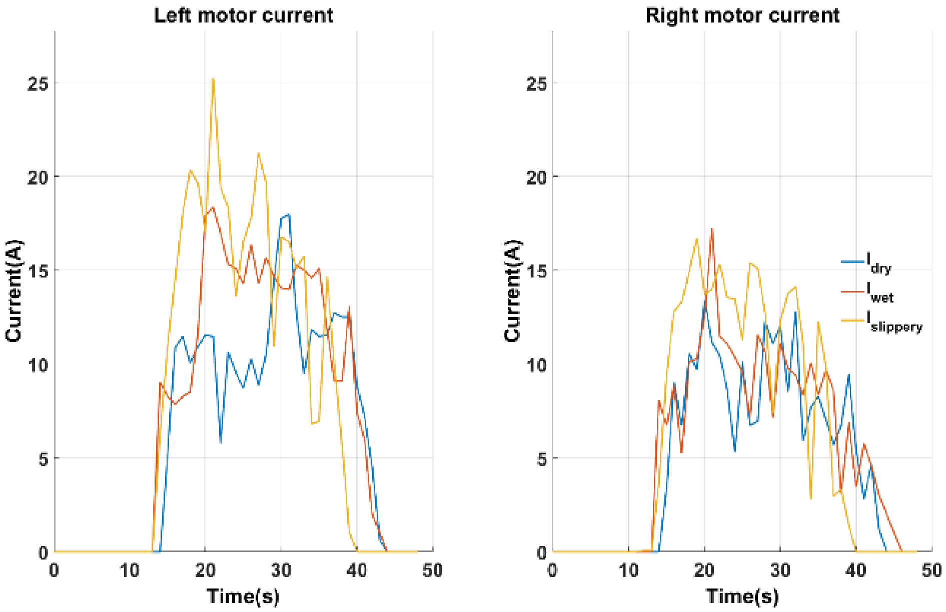


Figure 9. The motor current data on three different test areas at 5º right turn of the electric vehicle

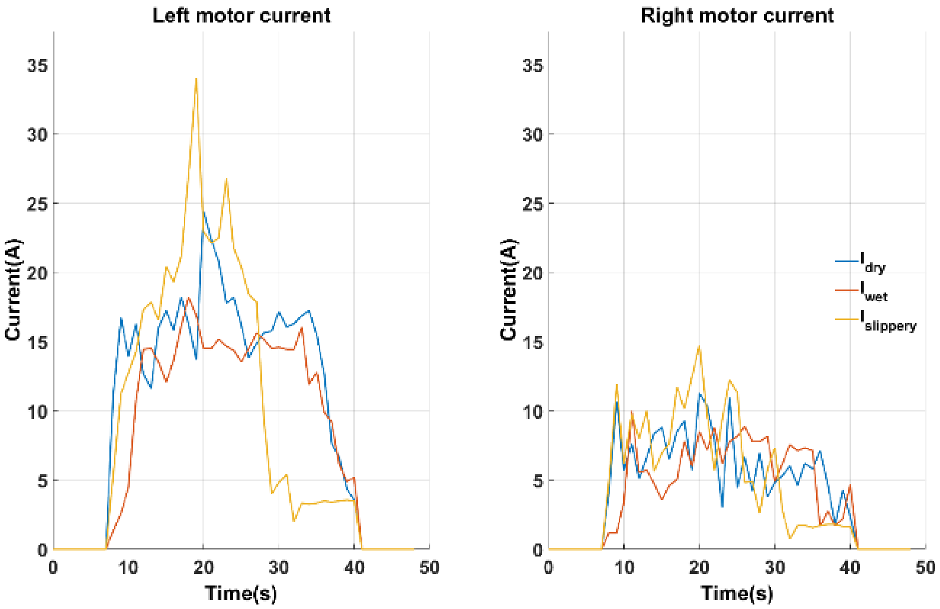


Figure 10. The motor current data on three different test areas at 15º right turn of the electric vehicle

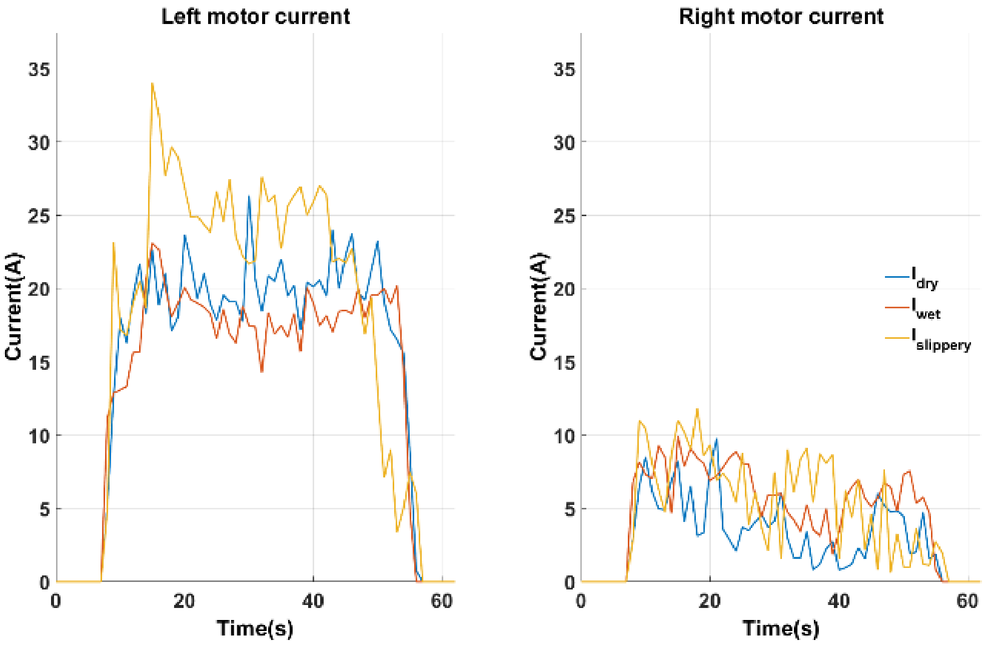


Figure 11. The motor current data on three different test areas at 25° right turn of the electric vehicle

According to the figures above, it is seen that the highest fluctuation and irregularity occurred in slippery road conditions. This may have occurred due to the reduced coefficient of friction between the wheel and the slippery test area. However, no degradation was detected in the engine speed data due to the EDS controller used.

6. CONCLUSIONS

This research article deals with an EDS-based electric vehicle created using AJT. The drive system in the electric vehicle is created by connecting directly to the wheels two separate DC motors. EDS reduces the components used in the vehicle's drive transmission, in other words, the mechanical differentil and gearbox are not used. As a result, overall reliability and efficiency are increased. In order to verify the theoretical and simulation results and demonstrate the suitability of EDS in terms of accuracy and stability, EDS was embedded on an ST microprocessor (STM32F103) and road tests were carried out. The performance of the created EDS has been investigated. It has been observed that the vehicle can maintain its balance while cornering and moving in three different road conditions.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods they use in their studies do not require ethics committee approval and / or legal-specific permission.

AUTHORS' CONTRIBUTIONS

İbrahim ÇELİK: Performed the experiments and analyses the results. Wrote the manuscript.

Güray SONUGÜR: Performed the experiments and analyses the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] V. Etacheri, R. Marom, R. Elazari, G. Salitra and D. Aurbach, "Challenges in the development of advanced Li-ion batteries: a review," ***Energy & Environmental Science***, 4(9): 3243-3262, (2011).

[2] C.-S. Wang, O. H. Stielau and G. A. Covic, "Design Considerations for a Contactless Electric Vehicle Battery Charger," ***IEEE Transactions On Industrial Electronics***, 52(5):1308-1314, (2005).

[3] S. F. Tie and C. W. Tan, "A review of energy sources and energy management system in electric vehicles," ***Renewable and Sustainable Energy Reviews***, 20(1): 82-102, (2013).

[4] İ. Çelik, Elektrikli Bir Araç İçin Elektronik Diferansiyel Simülatörün Modellenmesi ve Gerçek Zamanlı Uygulaması, Afyon: **Afyon kocatepe Üniversitesi**, (2019).

[5] K. Hartani, Y. Miloud and A. Miloudi, "Electric Vehicle Stability with Rear Electronic Differential Traction," in ***International Symposium on Environment Friendly Energies in Electrical Applications***, Ghardaia, Algeria, (2010).

[6] K. Hartani, M. Bourahla, Y. Miloud and M. Sekour, "Electronic differential with direct torque fuzzy control for vehicle propulsion system," ***Turkish Journal of Electrical Engineering and Computer Sciences***,17: 21-38, (2009).

[7] A. Haddoun, M. Benbouzid, D. Diallo, R. Abdessemed, J. Ghouili and K. Srairi, "Design and Implementation of an Electric Differential for Traction Application," in ***IEEE VPPC***, Lille, France, (2011).

[8] Eyyüp Ö., Burak T., Hasan K., Merve Y., "Electronic Differential System for an Electric Vehicle with In-Wheel Motor," in ***9th International Conference on Electrical and Electronics Engineering***, Bursa, (2015).

[9] R. P. d. Castro, H. S. Oliveira, J. R. Soares, N. M. Cerqueira and R. E. Araujo, "A new FPGA based control system for electrical propulsion with electronic differential," in ***European Conference on Power Electronics and Applications***, Aalborg, Denmark, (2007).

[10] H. J. G. G. Yiding Hua, "Electronic differential control of 2WD electric vehicle considering steering stability," in ***AIP Conference Proceedings***, (2017).

[11] N. S. Popov, V. N. Anosov, M. E. Vilberger, E. A. Domakhin, V. I. Anibroev and I. I. Singizin, "Development of autonomous traction system of electric vehicle with electronic differential and fuzzy control system," ***Journal of Physics: Conference Series***,1661(1): 012108, (2020).

[12] A. Nejh and H. Trabelsi, "Design of PMSMs Topologies Based on FEA for In-Wheel Motor Hybrid Propulsion Application," in ***12th International Multi-Conference on Systems****, Signals and Devices*, Mahdia, TUNISIA, (2015).

[13] C. Bharatiraja, J. Munda, I. Vaghasia, R. Valiveti and P. Manasa, "Low cost Real Time Centralized Speed Control of DC Motor Using Lab View -NI USB 6008," ***International Journal of Power Electronics and Drive System (IJPEDS)****,* 7: 656-664, (2016).

[14] M. Khristamto, A. Praptijantoa and S. Kalega, "Measuring geometric and kinematic properties to design steering axis to angle turn of the electric golf car," ***Energy Procedia****,* 68(1): 463-470, (2015).

[15] H. BAYRAKÇEKEN and M. DÜZGÜN, "Taşıtlarda Fren Verimi ve Frenleme Mesafesi Analizi," ***Journal of Polytechnic****,* 8(2): 153-160, (2005).