Skid Steering for Electric Vehicle as Fail Operational Steering Mechanism

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1. ABSTRACT

To achieve highly automated driving, vehicles are required to operate without driver-in-loop. This requires fail operational system for braking and steering. For fail operational Electric Power Steering(EPS) several suppliers have developed 2-drive technology, which uses two motor windings, two torque sensors and two inverter drive units. This paper has proposed use of skid steering in case of failure of EPS of vehicles. Skid steering involves changing the speed of the left and right wheels of a vehicle to achieve desired steering radius.

2. INTRODUCTION

NHTSA defines “highly automated vehicle(HAV)” as vehicles with SAE level 3-5 autonomy [1]. These vehicles are capable of monitoring their driving environment. Whereas in level 3 autonomy, driver can take back control after the driver has been alerted about system failure, in level 4-5 automated vehicles, the driver does not need to take control.

Currently in case of failure of Electric Power Steering(EPS), the motor driver is turned off and the system is reduced to mechanical rack and pinion steering. The driver is required to take control of vehicle in such cases.

Keeping in view requirements for level 4-5 autonomy, suppliers such as Bosch and Denso have developed 2-Drive technology for EPS [2]. These systems make use of two motor windings, two torque sensors and two inverter drive units. In normal scenario both the motor windings, torque sensors and inverters work. In case of failure the redundant unit takes control. This makes this system resistant to single-point failures and suitable for HAV.

In this paper, a system has been proposed which uses existing single drive EPS as primary steering mechanism. In case of failure skid steering is used to steer the vehicle. Whereas 2-drive EPS systems are capable of resisting failures associated with motor, drive unit and torque sensor, they are not capable of handing the mechanical damage that can happen to rack and pinion mechanism. Skid steering makes use of diverse actuation mechanism which can work even in case of failure to the rack and pinion system.

Currently Electric Vehicles(EV) are being developed which have individual traction motor for the wheels which has allowed the possibility of implementing skid control of vehicles [3]. Kececi et al have shown that skid control is capable of providing higher lateral forces thus enabling evasive maneuver and sharp turns [4]. Skid control of vehicle results in larger turning radius primarily due to wheel slip. In this paper slip limitation feedback controller as proposed by Shuang et al has been implemented [3]. The wheel slip is directly observed and accordingly the wheel speeds are modified using a PID controller. The tire model as proposed by Pacejka has been used [5]. A Simulink model has been implemented to verify the results. For tire and vehicle model Simscape Driveline libraries [6] have been used. The vehicle under consideration is front drive EV, with traction motor for each front wheel.

3. SKID STEERING

In this section, the turning radius has been described as a function of wheel speeds. The tire model and influence of wheel slip on the turning radius has been discussed. Further, the method of slip limitation feedback controller has been discussed.

3.1 TURNING RADIUS

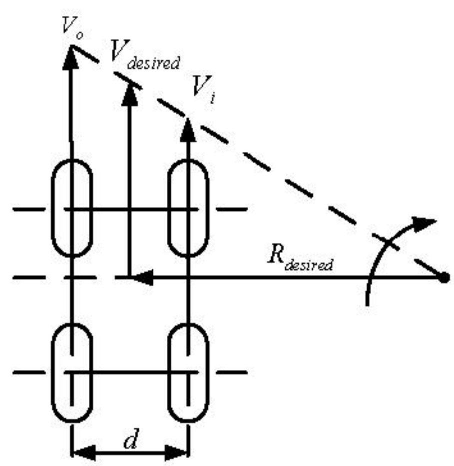

Fig 1: Turning radius and wheel speeds [3]

Using similar triangle relations, the relationship between the inner wheel speed(Vi), outer wheel speed(Vo), distance between tires and desired turning radius is obtained as follows:

$$Rdesired = \frac{\mathrm{Vo+Vi}}{\mathrm{Vo-Vi}} * \frac{\mathrm{d}}{2} \tag{1}$$

$$Vdesired = \frac{\mathrm{Vo+Vi}}{2} \tag{2}$$

3.2 TIRE MODEL

Tire Model is being used to represent the longitudinal behavior of highway tire as characterized by Magic Formula proposed by Pacejka [5]. It is called Magic Formula as a physical basis does not exist but is capable of modeling the tire behavior accurately. The formula is being stated as follows:

$$C = 1.65$$
$$D = a_1 F_z^{\,2} + a_2 F_z$$
$$BCD = \frac{a_3 F_z^{\,2} + a_4 F_z}{e^{a_5 F_z}}$$
$$B = \frac{BCD}{CD}$$
$$E = a_6 F_z^{\,2} + a_7 F_z + a_8$$

a1 = -21.3, a2 = 1144, a3 = 49.6, a4 = 226, a5 = 0.069, a6 = -0.006, a7 = 0.056, a8 = 0.486

Longitudinal Force is a function of the coefficients calculated above and percentage longitudinal slip, σ

$$\phi = (1 - E)\sigma + \frac{E}{B}\tan^{-1}(B\sigma)$$
$$F_x = D\sin\left(C\tan^{-1}(B\phi)\right)$$

Fig: Longitudinal Force Calculated using Tire Slip [7]

For modeling purposes, the tire model from Simscape Driveline library is being used.

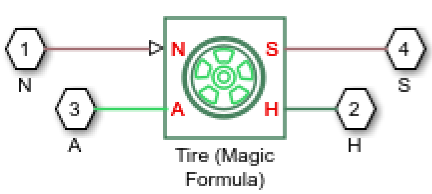

Fig 2: Tire Model for Magic Formula block from Simulink

This block incorporates the Magic Formula for tires. It takes as input the normal force acting on the wheel(N), torque applied to the wheel(A) and provides the tire slip(S) and the force transmitted to the wheel hub(H)

3.3 SLIP LIMITATION FEEDBACK CONTROLLER

In case of wheel slip the actual turning radius is larger than the desired radius. Actual radius is given by following expression:

$$Ractual = \frac{Vo*(1+So)+Vi*(1+Si)}{Vo*(1+So)-Vi*(1+Si)} * \frac{d}{2} \tag{3}$$

where so and si represent the slip ratio given by following expression:

$$Sx = \frac{Vx-\omega*R}{\omega*R} \tag{4}$$

where, Sx is the slip ratio for a wheel, Vx is the wheel speed of corresponding wheel, ω is angular speed of wheel, R is the radius of wheel.

In Skid Steering the wheel speed is varied to achieve the desired radius of turn. However, under the influence of wheel slip the radius of turn is larger than the desired radius. Slip feedback observes the wheel slip in real time and accordingly varies the reference wheel speed for outer and inner wheels to achieve the desired radius.

$$Vo\ ref = \frac{Vo}{(1+So)} \tag{5}$$

$$Vi\ ref = \frac{Vi}{(1+Si)} \tag{6}$$

4. SYSTEM CONFIGURATION

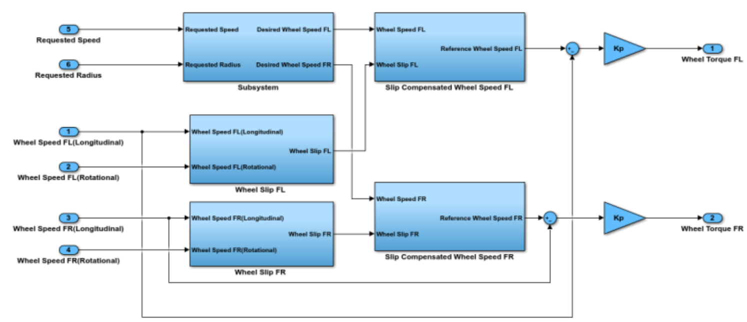

Fig 3: Skid Steering Block Diagram

Wheel slip is calculated from the longitudinal and rotational wheel speed. Using the requested speed and radius of turn the desired wheel speed for left and right front wheels is calculated. Using slip and desired wheel speed the reference wheel speed (slip compensated) is calculated. Proportional control uses the difference between reference and actual wheel speed and proportional gain to calculate the wheel torque.

5. SIMULATION MODEL

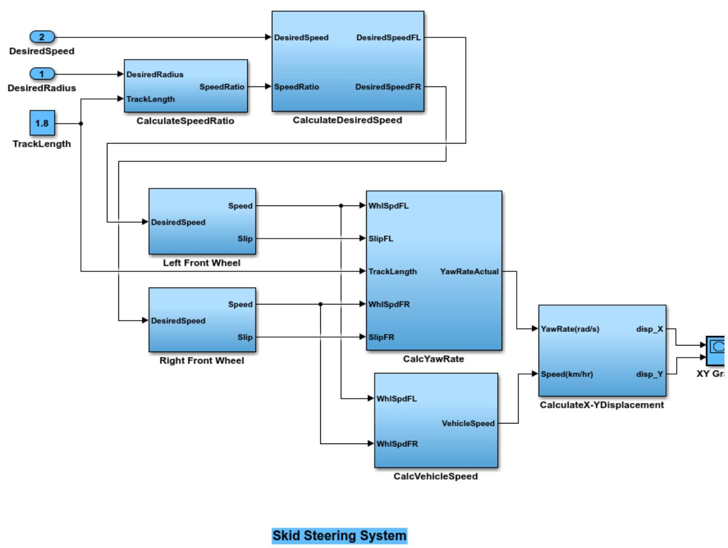

Fig 4: Skid Steering Simulation Model

5.1 CALCULATING SPEED RATE AND DESIRED SPEED FOR LEFT AND RIGHT WHEELS

Skid steering involves varying the speeds of inner and outer wheels to achieve desired radius of turn.

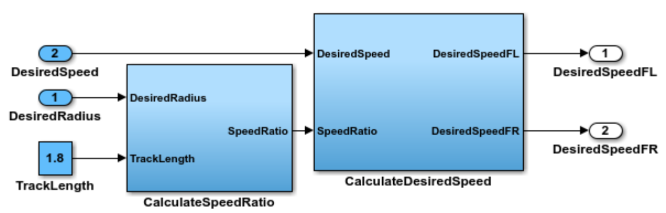

Fig 5: Model for calculating Desired Wheel Speeds

$$Speed\ Ratio, k = \frac{\mathrm{Rdesired} - \mathrm{d}/2}{\mathrm{Rdesired} + \mathrm{d}/2}$$

In terms of speed ratio, k the speeds for front left and front right wheels are obtained as follows:

$$Wheel\ Speed\ FL = \frac{2 * \mathrm{Vdesired}}{\mathrm{k} + 1}$$

$$Wheel\ Speed\ FR = \frac{2 * \mathrm{Vdesired} * \mathrm{k}}{\mathrm{k} + 1}$$

5.2 MODELING WHEELS TO OBTAIN SPEED AND SLIP

In order to understand the impact of skid steering the the vehicle has been modeled as two bicycle models one for left half and other for the right half.

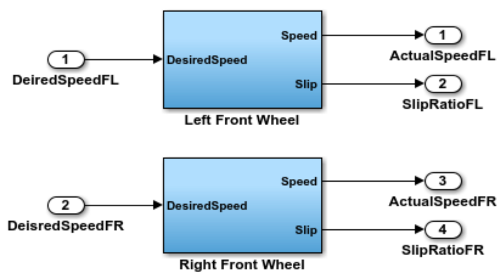

Fig 6: Model to calculate slip compensated Wheel Speeds

Model for Left Front Wheel

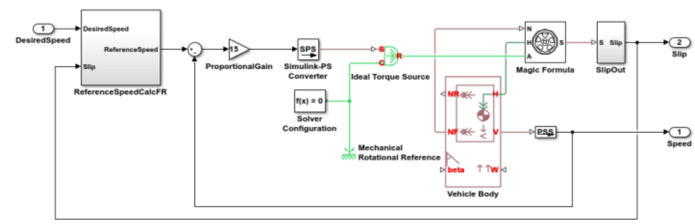

Fig 7: Model to simulate vehicle, controller and wheel

5.2.1 Calculation of Reference speed

The wheels undergo slip as a result of which the actual radius is greater than desired radius of turn. Thus, the wheel speed needs to be compensated for slip.

$$Vref = \frac{\mathrm{Vdesired}}{(1 + \mathrm{SlipRatio})}$$

5.2.2 Proportional Control and Torque Source

The reference wheel speed is subtracted from actual speed and multiplied by proportional constant to obtain desired torque for the wheel. The torque calculated by proportional control is converted to wheel torque using “Ideal Torque Source” block from Simscape Driveline library.

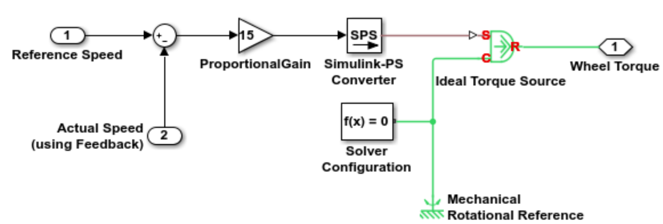

Fig 8: Model to simulate proportional control and torque source

5.2.3 Wheel and Half Vehicle(bicycle) model:

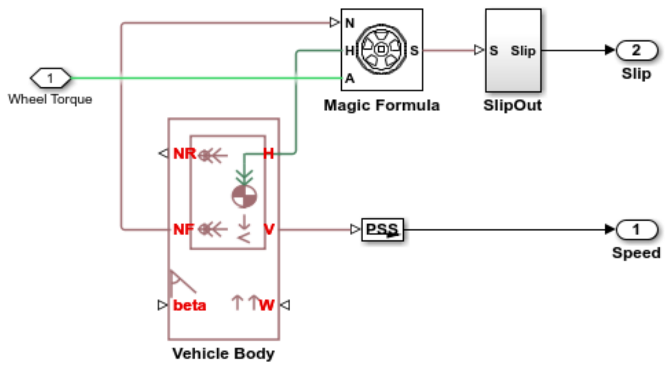

Fig 9: Model to simulate wheel and vehicle body

The wheel has been modeled using “Tire (Magic Formula)” and “Vehicle Body” components from Simscape Driveline.
The Tire (Magic Formula) component requires Normal Force(N) and Wheel Torque(A). Normal Force is provided as feedback from Vehicle Body component. In turn, the wheel component calculates slip ratio(S) and Hub Torque(H).
The vehicle body component takes the Hub Torque(H) calculated by Tire component and provides the Normal Force(N) and Speed(V).
Similarly, Right Front Wheel is modeled.

5.3 CALCULATE YAW RATE

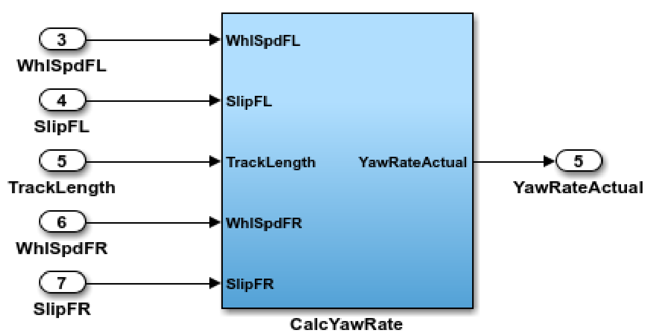

Fig 10: Model to calculate yaw rate

$$yaw\ rate = \frac{V_{fl} * (1 + Slip_{fl}) - V_{fr} * (1 + Slip_{fr})}{\mathrm{d}}$$

where, V_{fl} and V_{fr} are wheel speeds of front left and front right wheels respectively, $Slip_{fl}$ and $Slip_{fr}$ are the slip ratios of front left and front right wheels respectively, d is the track length of vehicle.

5.4 CALCULATE VEHICLE SPEED

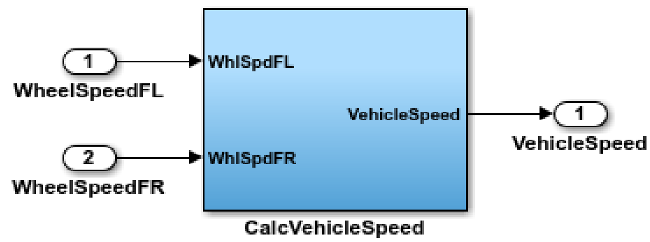

Fig 11: Model to calculate vehicle speed

The vehicle speed is average of the front left and front right wheel speeds.

5.5 CALCULATE X-Y DISPLACEMENT

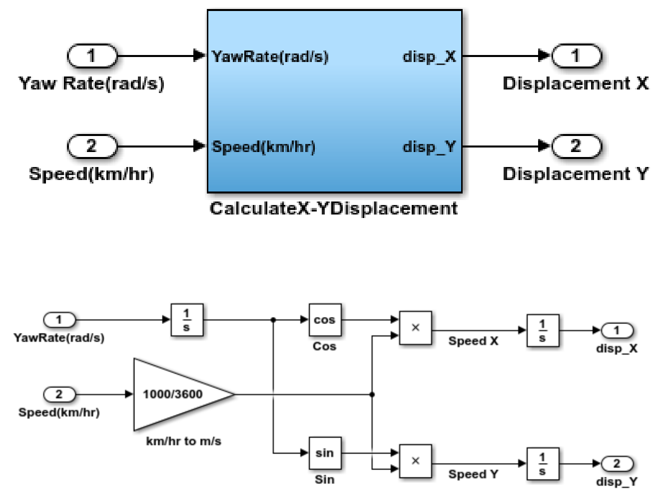

Fig 12: Model to calculate x-y displacement

Yaw rate is integrated to obtain orientation. The vehicle speed is converted to m/s and then using the orientation angle resolved into Speed along x and y directions. The speed along x and y are integrated to obtain the displacement along x and y axis.

6. SYSTEM DIAGNOSTICS

Functional Diagnostics

Failure in doing following functions should be reported as functional failure:
1. Lower speed for front left wheel should turn the vehicle left and lower speed for front right wheel should turn the vehicle right.
2. Yaw rate calculated using wheel speeds and wheel slip should equal to yaw rate being measured by yaw rate sensor.

Input Diagnostics

System should ensure that wheel rotational, longitudinal speeds and yaw rate are always available. This can be done by monitoring these signals for time out, CRC (cyclic redundancy check) and message counter. Also,

the wheel speeds should be monitored for being within valid limits.
Turn Radius Request Monitoring

The radius of turn request with vehicle speed should be monitored as it is possible that skid steering will not be able to maneuver the vehicle through some sharp turns. Failure Injection Testing can be done for vehicle to obtain limits for skid steering. It must be ensured that the systems working with skid steering comply to these limits.

7. EXPERIMENT

For a given vehicle speed, various radius values are requested and skid steering system is checked for following those radii.

Test Case 1: A vehicle speed of 60 kph and 80 m (right turn) is requested. Following trajectory plot is obtained:

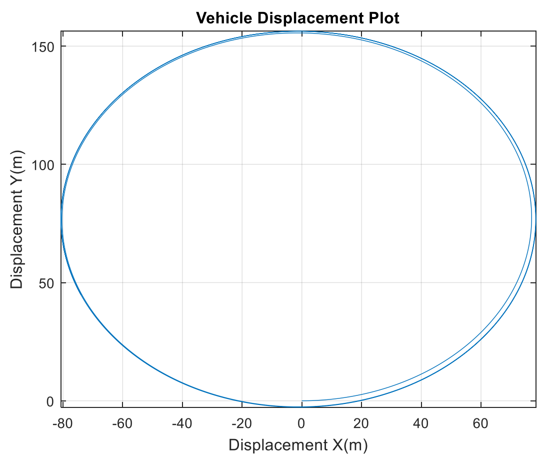

Fig 13: Test Case 1 – trajectory plot

It can be observed that path radius is 80 m as requested.
Following plot is obtained for desired speed for left and right wheels. Also, the slip compensated wheel speeds are obtained.

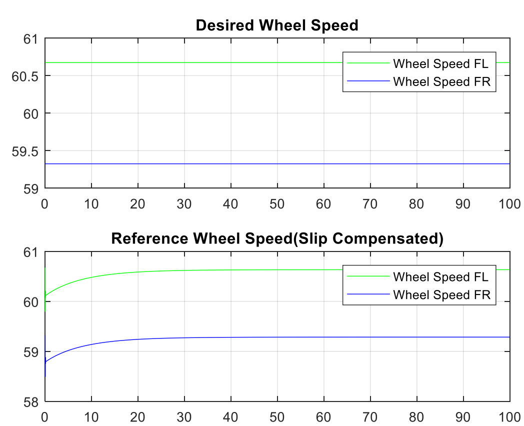

Fig 14: Test Case 1 – Desired and Slip compensated Wheel Speeds

As can be seen in this case the front left wheel speed is larger than front right as expected to negotiate right turn. Also in order to compensate for slip, the wheel speeds are increased.

Following plot is obtained for yaw rate:

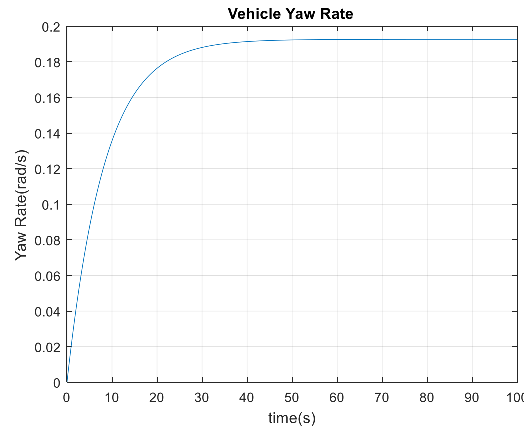

Fig 15: Test Case 1 – Yaw Rate

As can be seen that the yaw rate attains a constant value as expected for constant radius turn.

Test Case 2: A vehicle speed of 60 kph and radius of -80 m (left turn) is requested.

Following trajectory is obtained:

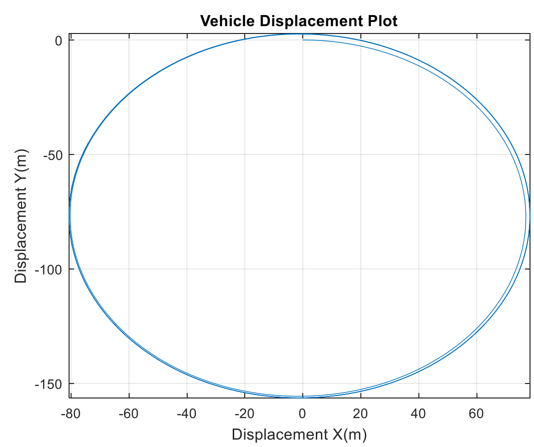

Fig 16: Test Case 2 – trajectory plot

Following plot is obtained for desired speed and reference wheel speed:

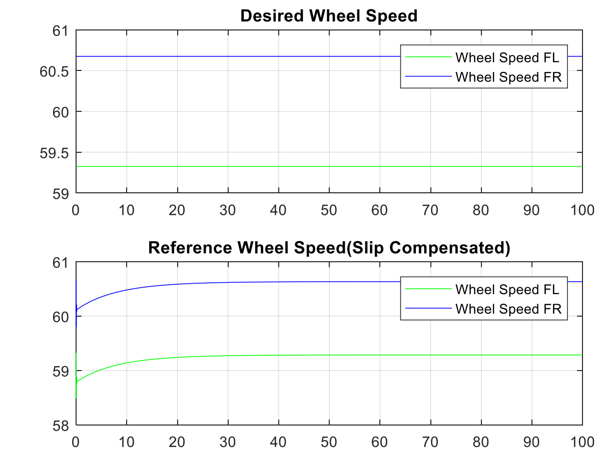

Fig 17: Test Case 2 – Desired and Slip compensated Wheel Speeds

As can be seen the right wheel speed is greater than left wheel speed.

Following plot is obtained for yaw rate:

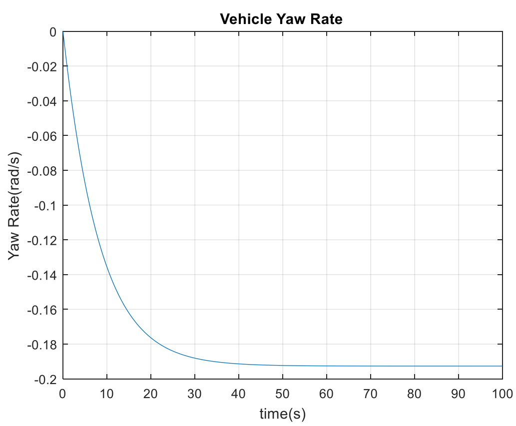

Fig 18: Test Case 2 – Yaw Rate

As can be seen the yaw rate is negative and attains a constant value as expected for constant radius turn.

CONCLUSION

In conclusion skid steering system for a vehicle with traction motors for front and left wheels has been presented theoretically and experimentally using simulation. This system has been proposed as a redundant steering mechanism for SAE level 4-5 fail operational systems. This system is required to take control of the vehicle in case of failure of Electric Power Steering. Vehicle model has been created using two bicycle models for left and right halves of vehicle. Slip feedback has been used to modify the wheels speeds. Using test cases, it has been verified that the system follows the requested radius trajectory.

ACKNOWLEDGMENTS

This project has been taken as a course requirement for ECE-533 Active Safety System as part of Master's program in Electrical Engineering at University of Michigan-Dearborn. Author would like to thank Prof Randy Boone, for all the informative and detailed classes taken as part of this course.

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Appendix

Vehicle Parameters Used for Simulation:

Mass of Vehicle	2400 kg
Horizontal distance from CG to front axle:	1.4 m
Horizontal distance from CG to rear axle:	1.6 m
CG height above ground:	0.5 m
Gravitational acceleration:	9.81 m/s^2
Rated vertical load for tire:	3000 N
Peak longitudinal force at rated load for tire:	3500 N
Slip at peak force at rated load (percent) for tire:	10
Radius of wheel	16*2.54/100 m
inertia lateral for wheel	25*(radius of wheel)^2 kg*m^2
tire stiffness	200000 N/m
tier damping	1000 N/(m/s)