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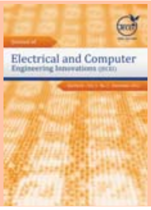

Driving/Regeneration and Stability Enhancement of a 4WD Hybrid Vehicles Using Multi-Stage Fuzzy Controller

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ABSTRACT

In front wheels driven vehicles, fuel economy can be obtained by summing torques applied to rear wheels. On the other hand, unequal torques applied to rear wheels provides enhanced safety. In this paper, a model with seven degrees of freedom is considered for the vehicle body. Thereafter, power-train subsystems are modeled. Considering an electrical machine on each rear wheel, a fuzzy controller is designed for each driving, braking, and stability conditions. Another fuzzy controller recognizes the vehicle requirements between the driving/regeneration and stability modes. The simulations performed in MATLAB/Simulink environment show that the proposed structure can effectively enhance vehicle performance in different modes.

1. INTRODUCTION

One of the significant qualitative factors of the vehicle behavior is its stability in critical driving conditions such as braking on μ-Split road and rotation with high speed. Recent research results of fuel economy in vehicles have led to invention of hybrid vehicles. In these vehicles, driver power demand is provided by gasoline engine and electrical machine. In most research works the goal of control strategy is only based on fuel economy. In [1], a model based on the real time road control strategy was offered for parallel hybrid vehicles. An optimal control strategy that chose power split between the engine and electrical machine was presented in [2] to minimize fuel consumption in parallel hybrid vehicles. In [3], fuel economy was improved using field oriented control of a permanent magnet motor and its belt coupling with crankshaft. A simulation program was given in [4] to simulate behavior of various components of hybrid vehicles. Some studies have focused on the vehicles' stability. A driver-assist stability system and stability enhancement for all-wheel-drive electric vehicles has been introduced in [5-7]. This system was proposed in [8] for two-motor-drive electric vehicle to enhance safety using a fuzzy logic based controller. In [9], using an electrical machine on front and rear axles, stability enhancement and regenerative braking were provided. Direct yaw rate control with road condition estimation and anti-slip control have been proposed in [10]. In [11], for an electrical vehicle, a new estimation method of slip-rate has been presented.

2. PROPOSED STRUCTURE

In a front differential vehicle, unequal torques applied to rear wheels will bring vehicle dynamic control to path correction. On the other hand, summation of torques is an essential factor in power managing among engine and electrical machines. Figure 1 shows the proposed structure. Beside battery state of charge (SoC), other input signals are necessary which will be illustrated in the following parts.

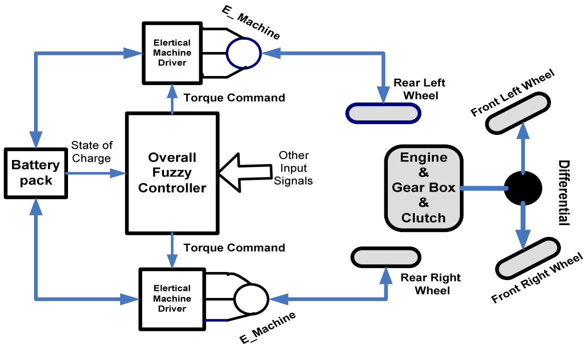

Figure 1: The proposed structure and controller

3. VEHICLE MODELLING

A. *Body modeling and tire forces*

A model with seven degrees of freedom was used for simulation. In this model, the system dynamic can be described as follows [6]:

$$M_t(\dot{u} - rv) = F_{xfl}\cos\delta - F_{yfl}\sin\delta + F_{xfr}\cos\delta + F_{yfr}\sin\delta + F_{xrl} + F_{xrr} - F_{ax} \quad (1)$$

$$M_t(\dot{v} + ru) = F_{xfl}\sin\delta + F_{yfl}\cos\delta + F_{xfr}\sin\delta + F_{yfr}\cos\delta + F_{yrl} + F_{yrr} - F_{ay} \quad (2)$$

$$\begin{aligned} I_z\dot{r} = {} & L_f\left[F_{xfl}\sin\delta + F_{yfl}\cos\delta + F_{xfr}\sin\delta + F_{yfr}\cos\delta\right] - L_r\left[F_{yrl} + F_{yrr}\right] \\ & + \frac{T}{2}\left[F_{xfl}\cos\delta - F_{yfl}\sin\delta - F_{xfr}\cos\delta + F_{yfr}\cos\delta + F_{xrl} - F_{xrr}\right] + M_{zfl} + M_{zfr} + M_{zrl} + M_{zrr} \end{aligned} \quad (3)$$

Three degrees were devoted to the chassis' motion and four degrees were assigned to wheels' angular speed. fl, fr, rl and rr denoted front left, front right, rear left and rear right, respectively.

Symbol	Definition
F_x	Wheel's longitudinal force
F_x	Wheel's lateral force
F_R	Wheel's rolling resistance force
F_a	Aerodynamic drag force
X,Y	Denotation to static reference frame
x,y	Denotation to moving reference frame
δ	Steer angle
CG	Corresponding to center of gravity
L_f	Distance from CG to front axle
L_r	Distance from CG to rear axle
T	Long of vehicle axle
u	Longitudinal velocity of CG
v	Lateral velocity of CG
r	Vehicle yaw rate
M_z	Wheel's self-aligning torque
M_t	Vehicle total mass

B. *Tire modeling*

Tire modeling is one of the most important and ambiguous parts of vehicle modeling. By applying mover torque (τ_w) to the wheel, the rotation can be described as follows:

$$I_{wi}\dot{\omega}_i = \tau_{wi} - R_w F_{xi} - \tau_{Ri} \quad \text{for} \quad i: \text{fl, fr, rl, rr} \quad (4)$$

where I_w and R_w are wheel's moment of inertia and wheel's radius, respectively, ω is wheel's angular speed, and τ_R is wheel's rolling resistance torque, which is an important factor in computing fuel consumption.

$$\tau_R = C_0F_z + C_1|V_w|^2 \quad (5)$$

V_w is wheel's linear speed and usually $0.04 \le C_0 \le 0.2$, $C_1 << C_0$. Well known Dugoff's model for longitudinal and lateral forces is used in this article [12]. F_z is vertical force on the tire considering effects of vehicle longitudinal and lateral accelerations and can be obtained by the known formulas mentioned in [6].

C. *Power transmission system modeling.*

Transmission subsystem includes engine, gear box, clutch, brake, and differential. The output engine power is transferred to driven wheels via clutch, gear box, and differential. Braking torque is transferred to all wheels directly by the brake pedal command. On account of the equality between input and output power in gear box and differential systems, modeling of these subsystems can be performed by assuming a constant coefficient for each of them. Engine and gear box speed equivalency is assumed for simulation purposes. Since this regulation would be violated in some cases such as low speed motion or driving by improper gear, the engine power will be wasted in clutch subsystem. Figure 2 shows transmission modeling. Figure 3 shows clutch power transmission curve which is utilized in this work for simulation. The clutch is simulated by two surfaces. One of them is connected to engine shaft and another is jointed to gear box input.

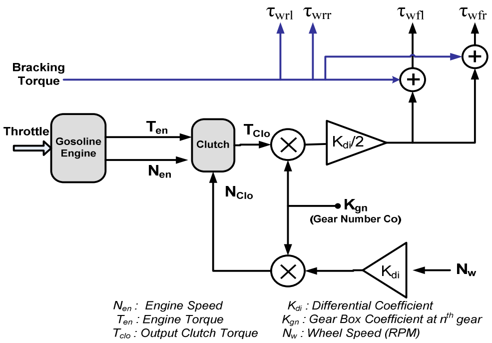

Figure 2: Mechanical power flow modeling

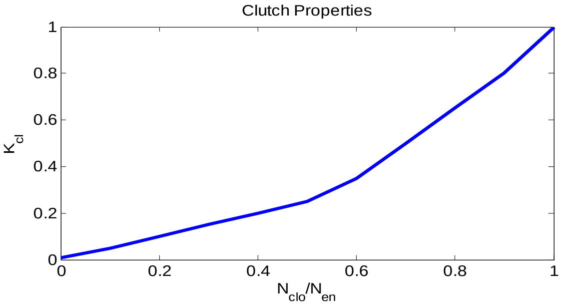

Figure 3: Clutch model curve

In Figures 2 and 3:

Symbol	Definition
K_{GN}	The nth gear coefficient
K_{DI}	Differential gear coefficient
N_{EN}	Engine shaft speed
T_{EN}	Engine output torque
N_{CLO}	Gear box speed at the n^{th} gear
T_{CLO}	Output torque of gear (n^{th} gear)
$K_{CL}=T_{CLO}/T_{CLI}$	Clutch coefficient

Engine torque and fuel consumption will be computed regarding engine maps for modeling purposes. One of these maps computes shaft torque based on throttle opening and shaft speed. The engine fuel consumption is determined according to shaft speed and shaft torque. Due to previous discussion, the shaft speed will be related to the vehicle speed in usual conditions. Also, driver power demand will be implemented by throttle and brake pedals in positive and negative accelerations, respectively. Figures 4 and 5 show the engine maps employed for simulation taken from 'ADVISOR' simulation program [13]. Considering Figure 4, engine output torque is negative in some cases. This case happens due to engine power shortage compared with wheels' power in downhill driving condition, for example. This is a key note for power regeneration simulation when there is no pressure on brake pedal.

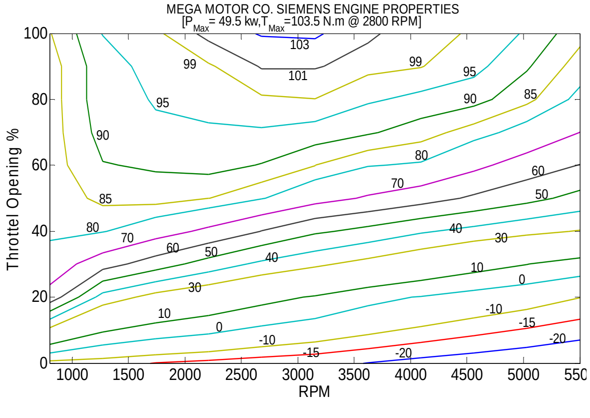

Figure 4: Engine's torque map

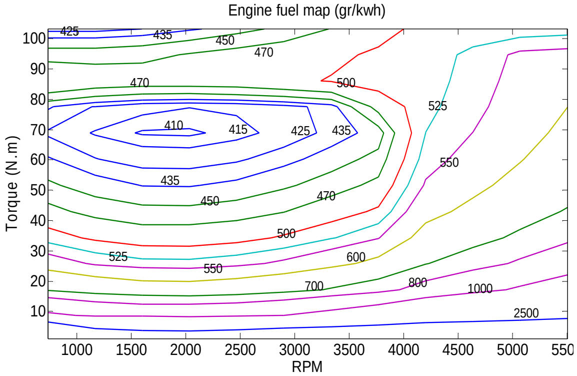

Figure 5: Engine's fuel consumption map

4. Modelling of Electrical Components

Electrical subsystems, used in this article, consist of AC/DC converter, electrical machine, batteries, and power electronic components. Because of fast dynamicity of these subsystems in comparison with vehicle dynamics, only the battery's dynamic model is taken into account. In this way, the 'ADVISOR' statistical model is used for Inverter/Electrical machine modeling [13]. The models demonstrated above are utilized in simulation part.

4.1. *Inverter/Electrical machine modeling*

In electrical machine and connected inverter models, efficiency and maximum rotor torque are available. Figure 6 shows Inverter/Electrical machine maps for modeling.

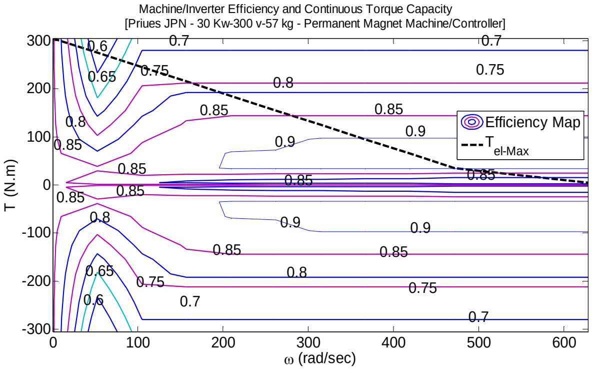

Figure 6: Electrical machine curves

4.2. *Battery modeling*

Battery state of charge (SoC) is the most important control signal in the hybrid vehicle. In this paper, one of the well-known battery models is employed. This model is based on variable voltage source and internal variable resistance depending on SoC. Figures 7 and 8 show this model and typical values of its parameters [13]. One of the simple and well known formulas for SoC calculation is given below: where SoC(0) is initial state of charge, Ah_{cap} and Ah_{used} are maximum and used battery Amper×hour, respectively, and I_b is instantaneous battery current.

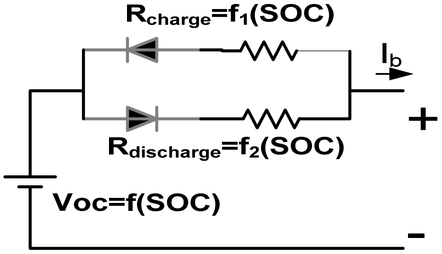

Figure 7: The 'R_Internal' battery model

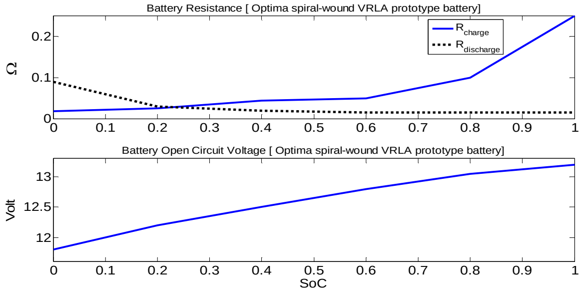

Figure 8: internal parameters of Battery

$$\mathrm{SoC} = \frac{(\mathrm{Ah_{cap}} - \mathrm{Ah_{used}})}{\mathrm{Ah_{cap}}} \qquad (10)$$

$$\mathrm{Ah_{used}} = \mathrm{Ah_{cap}}(1 - \mathrm{SoC_{(0)}}) + \int_0^t \frac{\mathrm{I_b}}{3600}\,\mathrm{dt} \qquad (11)$$

5. DRIVER MODELING

A simple PID controller is used for driver behavior simulation in Throttle/Brake pedals' pressure. In addition, for gear changing simulation, it is assumed that the change established upon throttle opening and vehicle speed experimental data.

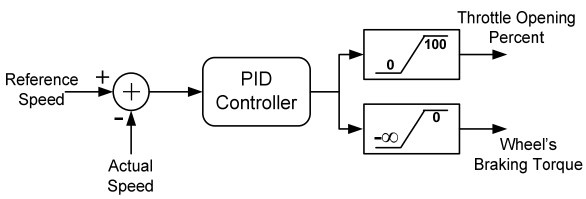

Figure 9: Simple PID controller for pedals' pressure simulation

6. CONTROLLER STRUCTURE AND STRATEGY

Regarding (3), the yaw rate can be directly controlled by applying a differential input torque to non-driven wheels (Fxrl-Fxrr). According to the steady state cornering theory of bicycle model, it is known that the vehicle velocity and yaw rate error satisfy the following equations [6].

$$r_d = (\frac{V_s}{L_f + L_r})\delta \qquad (12)$$

$$e_r = r_d - r \qquad (13)$$

Moreover, Driving/Regeneration braking can be obtained by summing torques applied to rear wheels which are called assistant forces (F_{xrl}+F_{xrr}). Overall controller consists of four sub-controllers, as shown in Figure 10. As could be seen in this figure, the braking mode control will be activated by brake pedal pressure.

Furthermore, in the driving condition, the assistant torque is evaluated on account of battery state of charge, vehicle speed, and mechanical torque enforced on front wheels. The Assistant/Regenerative torque generated by electrical machines may be near maximum torque capacity. In this case, if the yaw rate error exists, applying the computed torque by the stability mode sub-controller will be impossible. In order to solve this problem, the above mentioned goals are weighted by goal management sub-controller. Additionally, overall control operation will be activated only when the speed of vehicle is non-zero.

Controller structure, fuzzy membership's functions and rule bases are presented as follows. The symbols and definitions used in Figure 10 are noted in the following table.

Symbol	Definition
Gn	Gear number
V_s	Normalized vehicle speed
X_{bp}	Normalized brake pedal displacement
Th%	Throttle opening percent
τ_{Rotor_l}	Left machine torque
τ_{Rotor_r}	Right machine torque
τ_{el_max}	Maximum torque capacity of electrical machine
τ_{mech_drive}	Total of applied torque to front wheels
τ_{com}	Electrical machines torque command

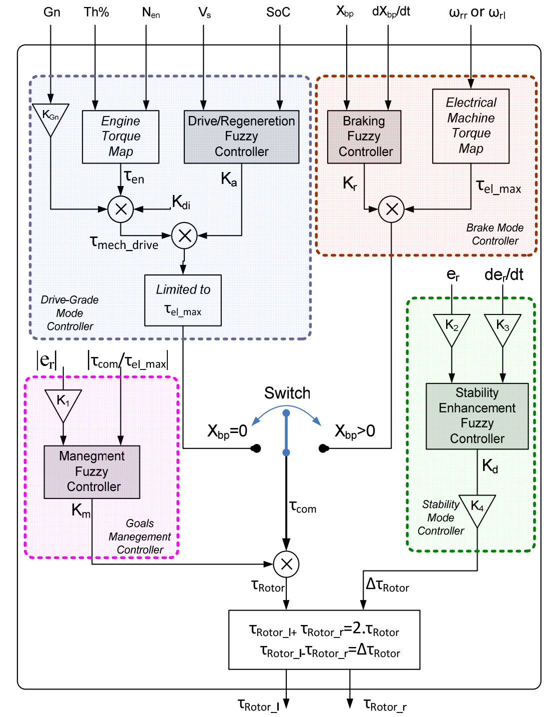

Figure 10: Controller structure

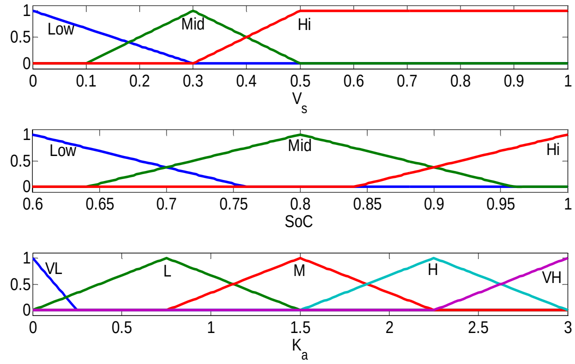

Figure 11: Drive-Grad fuzzy controller memberships

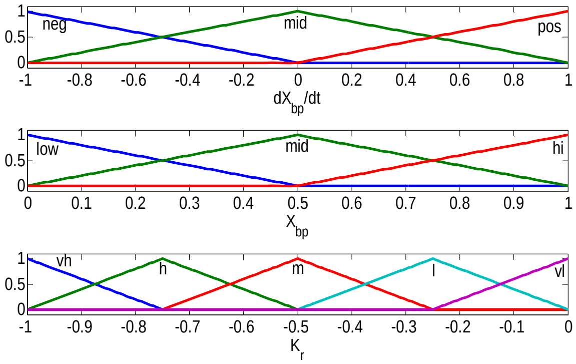

Figure 12: Braking fuzzy controller memberships

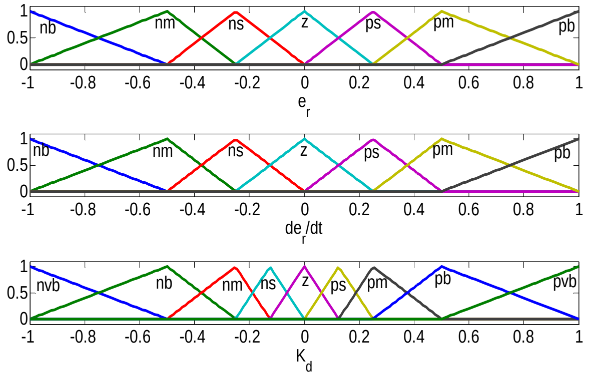

Figure13: Stability fuzzy controller memberships

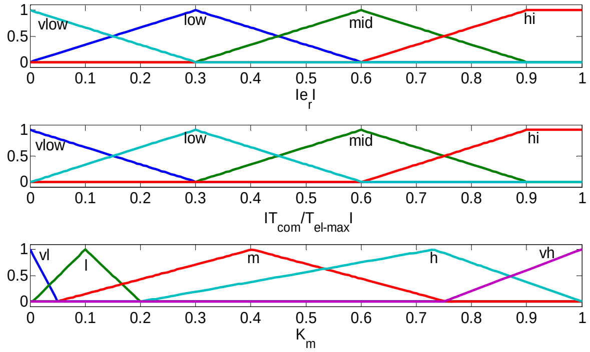

Figure 14: Goals management controller memberships

TABLE 1
FUZZY ROLL BASE OF EACH SUB-CONTROLLER

STABILITY MODE RULE BASE		e_r						
		NB	NM	NS	Z	PS	PM	PB
de_r/dt	NB	NVB	NVB	NVB	NB	NM	NS	Z
	NM	NVB	NVB	NB	NM	NS	Z	PS
	NS	NVB	NB	NM	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PM	PB	PVB
	PM	NS	Z	PS	PM	PB	PVB	PVB
	PB	Z	PS	PM	PB	PVB	PVB	PVB

DRIVE MODE RULE BASE		V_s		
		Low	Mid	Hi
SoC	Low	VL	VL	VL
	Mid	H	M	L
	Hi	VH	H	M

BRAKE MODE RULE BASE		dX_{bp}/dt		
		Pos	*mid*	*neg*
X_{bp}	*hi*	Vh	h	m
	mid	H	m	l
	low	M	l	vl

GOAL MANAGMENT RULE BASE		$\lvert\tau_{com}/\tau_{el\_max}\rvert$			
		Vlow	*low*	*mid*	*hi*
$\lvert e_r\rvert$	*vlow*	Vh	vh	vh	vh
	low	Vh	vh	h	m
	mid	Vh	h	m	l
	hi	Vh	m	l	vl

7. SIMULATION RESULTS

Certain parameters of an automobile called 'PRIDE' are tabulated below for the simulation

TABLE2
GEAR BOX DATA

Gear #	Coefficient	Symbol
1	3.454	K_{g1}
2	1.944	K_{g2}
3	1.275	K_{g3}
4	0.861	K_{g4}
5	0.6920	K_{g5}

TABLE 3
APPROXIMATELY CHANGED PARAMETERS

Parameter	Symbol	Unit	Value
Vehicle total mass	M_t	Kg	1460
Distance from front axle to CG	L_f	m	1.397
Distance from rear axle to CG	L_r	m	0.947

TABLE 4
BODY, WHEELS AND DIFFERENTIAL PROPERTIES

Parameter	Symbol	Unit	Value
Vehicle total mass	M_t	Kg	1160
Distance from front axle-CG	L_f	m	1.297
Distance from rear axle-CG	L_r	m	1.047
Track width	T	m	1.4
Drag coefficient	C_d	$N.s^2/m^2$	0.41
Frontal area	A_F	m^2	1.8
Lateral area	A_L	m^2	4.5
Vehicle inertia about z axis	I_z	Kgm^2	1809
Differential coefficient	K_d	No unit	3.78
Wheel's longitudinal stiffness	C_x	N	17500
Wheel's lateral stiffness	C_y	N/rad	15000
Wheel's radius	R_w	m	0.272
Wheel's inertia	I_w	Kgm^2	3.264

After installing electrical components which change vehicle into a hybrid one, some parameters will change, as shown in Table 3. In the next step, various scenarios will be simulated and the comparison will be done in order to evaluate the proposed structure's performance.

7.1. *Power management examination in civic driving cycles*

Three standard driving cycles which are shown in Figure 15 were used for simulations [13]. Engine behavior, battery operation, electrical machines torques, and braking torque for 'INDIA' driving cycle are shown in Figures 16-18. Fuel consumption of all of these three driving cycles is given in Table 5.

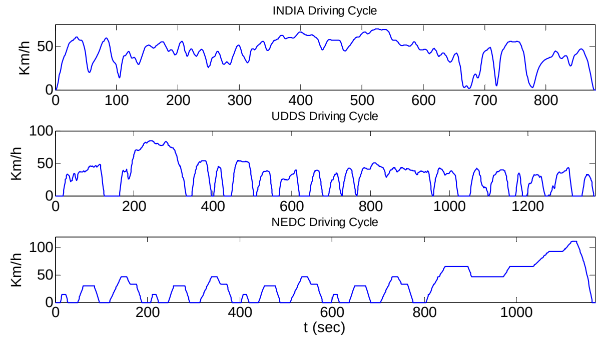

Figure 15: Civic driving cycles

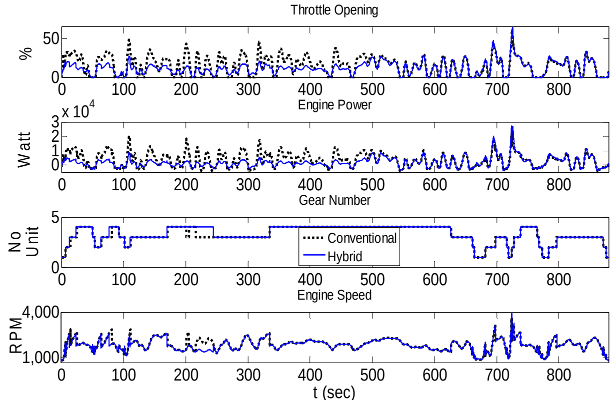

Figure 16: Engine behavior and gear changed in the 'INDIA' cycle

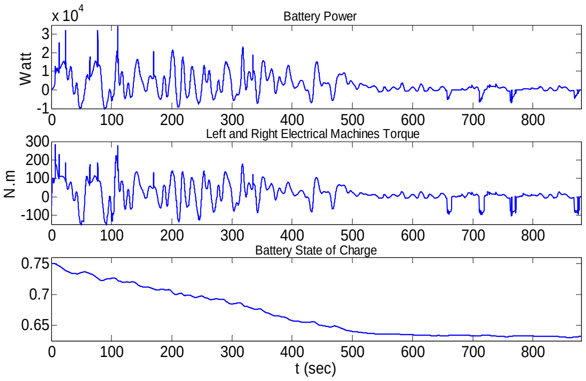

Figure 17: Battery behavior and electrical torques for the 'INDIA' cycle

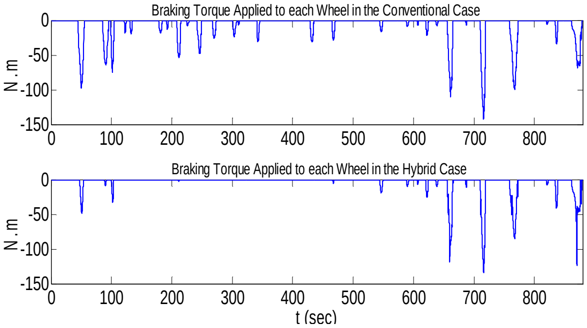

Figure 18: Braking torque applied in the 'INDIA' cycle

TABLE 5
FUEL CONSUMPTION

Driving Cycle	CONVENTIONAL Litre/(100 Km)	HYBRID Litre/(100Km)	FUEL ECONOMY
INDIA	6.33	4.31	31.9%
UDDS	8.28	6.33	23.5%
NEDC	8.19	5.11	37.6%

According to Figure 16, the engine output power in hybrid case is lower than the conventional one. Also, noticing the vehicle speed and battery output power, shown in Figure 17, when the vehicle speed increases between 350 to 600 sec, participation of electrical machines in power demand will be decreased by the controller. As seen in Figure 18, the vehicle in hybrid case has lower enforced braking torque which is corresponding to regenerative braking condition.

7.2. *Lane change with high speed*

Lane change maneuver results at 70 Km/h on normal road are illustrated as follows. It was assumed that driver applied the same steering effort in both conventional and hybrid vehicles. As depicted in Figure 19, the vehicle in hybrid case is more stable and the yaw rate is very close to the reference value.

7.3. *Braking on μ-split road*

In this section, braking at 110 km/h on a μ-split road (corresponding to dry pavement, μ=0.95, on the right side and unpacked snow, μ=0.35, on the left) was simulated. During the simulation, the steer angle was assumed to be zero. The vehicle speed reduction and simulation results are depicted in Figure 20. This figure shows that the hybrid vehicle has better stability during braking and the undesired lane change is also lower than the conventional one.

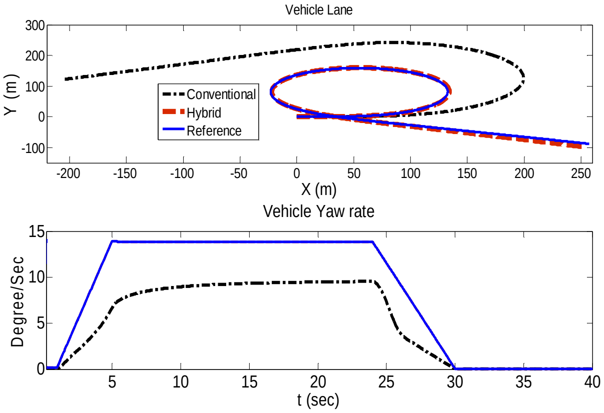

Figure 19: Yaw rate and vehicle lane during of lane changing

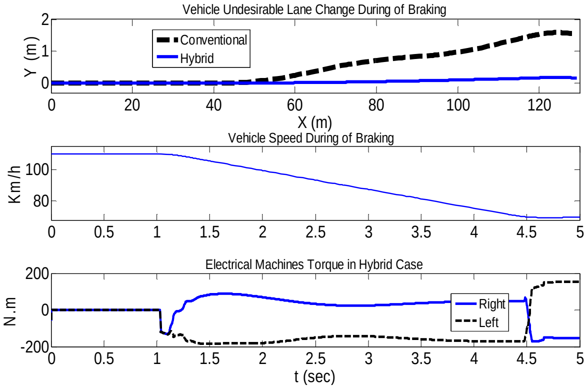

Figure 20: Vehicle speed, vehicle lane and electrical machines torque during of braking

8. CONCLUSION

In this paper, a driver-assistant stability system with Driving/Regeneration braking was introduced for a front differential vehicle using electrical traction system on rear wheels. Intelligent performance of the overall control system in making electrical machines' torque commands based on the driving necessities was the main advantage of the proposed controller. The simulation results showed intelligent performance of the proposed control system in various driving environments such as slippery roads.

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BIOGRAPHIES

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He is an author of many international papers and had written some technical books. He were also directed some research projects in Azerbaijan Electrical Utility of Iran. He is currently lecturing in Azarbaijan Shahid Madani University as a assistant professor. He is experienced many years of lecturing and researching in many of the fields in related with electrical power. He have had eighteen years of experience in industrial working in the field of power and energy