EVS30 Symposium
Stuttgart, Germany, October 9 - 11, 2016

Fundamental Research on Collision Force Reduction Control for In-wheel-motor EVs

Tomoki Emmei[1], Hiroshi Fujimoto[1], Yoichi Hori[1]
[1]*The University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba, Japan, enmei14@hflab.k.u-tokyo.ac.jp*

Abstract

In this paper, we propose ”active” collision damage reduction system, which has been regarded as difficult in the past, by using In-Wheel Motor (IWM) and aim to reduce collision damage during the offset collision. In order to mitigate the damage of a car accident, a ”passive” collision damage reduction system has been used. However, in the case like an offset collision, the reduction of the accident damage by the passive system cannot be expected. Therefore, we show that accident damage can be reduced actively with IWM by preliminary experiments and simulations.

1 Background

Although the number of traffic accidents tends to decrease with the development of automobile technology, the number of accidents occurring in 2016 is 500,000 cases in Japan alone, and nearly 4,000 people have died. In recent years, researches on automatic driving have been actively carried out and a number of the emergency avoidance technologies has been established[1, 2, 3]. However, it is extremely difficult to eradicate traffic accidents and techniques to reduce the collision damage are still of great importance. In general, in order to protect passengers, a ”passive” method is adopted, e.g. implementing a crushable zone in the front area of vehicle to reduce collision damage[4]. In case of the frontal collision, the ”passive” method is effective to protect the occupant. The front side member, which is the structure of the front part of the vehicle, was designed to collapse successfully in such a way as to alleviate the impact of a crash.

Recently, however, so-called ”offset collision”, in which obstacles pass through the sides without hitting this front side member, attracts attention. Conventional passive methods are not effective because offset collision gouges the outer edge of the vehicle where front side member does not exist. Therefore, new measures to protect passengers from impact are required.

Under such circumstances, it has been considered to be difficult to reduce accident damage ”actively”, which means to drive the wheels so as to avoid such a collision. Since the resonance frequency of the drive shaft is about several Hz, it is difficult to implement active collision damage reduction system which requires high speed control.

On the other hand, since the drive shaft is not used for In-Wheel Motor Electric Vehicles (IWM-EVs), it is possible for them to perform high speed control over dozens of Hz[5]. This suggests the possibility that driving force can be generated until the collision ends and accident damage can be actively reduced by using IWM.

In this research, in particular, we proposed a control method to reduce the collision force actively by taking something like ”ukemi” (break fall) of judo after detecting the offset collision, using the high control bandwidth of the IWM vehicle. In ”ukemi” control, the direction of the vehicle is changed in order to pass the collision force and reduce the damage of the accident. In this paper, we made a basic study through preliminary experiments and confirmed the effectiveness of the proposed method by simulations.

Table 1: Vehicle parameter of FPEV2-kanon.

Parameter	Value
Vehicle mass M	870 kg
Yaw moment inertia I	617 kg·m^2
Wheel base l	1.7 m
Distance between center of gravity and front wheels l_f	0.999 m
Distance between center of gravity and rear wheels l_r	0.701 m
Cornering stiffness of front wheels C_f	12500 N/rad
Cornering stiffness of rear wheels C_r	29200 N/rad
Tread width of front wheels d_f	1.3 m
Tread width of rear wheels d_r	1.3 m
Inertia of a front wheel J_f	1.24 kg·m^2
Inertia of a front wheel J_r	1.26 kg·m^2
Tire radius r	0.302 m
Height of center of gravity h_g	0.51 m
Maximum torque of front wheels T_{fmax}	625 Nm
Maximum torque of rear wheels T_{rmax}	530 Nm

2 Proposal: collision force reduction control with ”ukemi”

In this section, we propose to shift the collision point by rotation and reducing the damage of the collision like ”ukemi” of judo. We assume that the position of the collision point can be detected by various onboard sensors. Therefore, in the proposed method, by retracting the side surface close to the hitting point and propelling the far side surface, the car body is rotated to mitigate the collision force.

3 Pivot turn for IWM-EV

IWM-EVs can independently drive each wheel and can change the direction of the vehicle body without changing its center of rotation by generating opposite driving force between the left and right wheels[6]. Since the collision force mitigation control by ”ukemi” utilizes this property, simulation and basic experiment of the direction change is performed.

3.1 Experimental vehicle

The specification of the experimental EV is given in Table 1. The vehicle used in this study is FPEV2-Kanon (hereinafter referred to as ”experimental vehicle”), manufactured by authors’ research group. Experimental vehicle has four outer-rotor type in-wheel motors and each wheel can be independently controlled. Since no reduction gears and no gear backlash are present in the units, the motors can drive the wheel directly.

3.2 Simulation of pivot turn

First, we simulated the direction change by using the experimental vehicle. A simulation of one second was made by adding the maximum torque in the reverse direction to the left and right wheels of the stationary state: that is, 625 Nm for the front and rear wheels on the right side and -625 Nm for the front and rear wheels on the left side. In this simulation, the delay of the current control system (control band 1 kHz) is considered. The simulation result is shown in Fig. 1. The pentagon represents the direction of the vehicle and plots the vehicle attitude every 0.1 seconds from blue to brown. It rotates 163.67 degrees per second.

3.3 Preliminary experiment of pivot turn

We conducted a preliminary experiment. It consists in changing the direction of the site by simulating the situation of passive control. Assuming that a four-wheel independent IWM car collided, and that front-rear weight balance of the vehicle aside, the load is biased to the front wheel side due to rapid

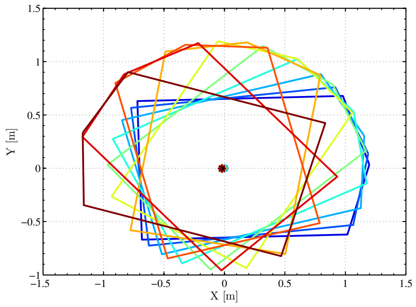


Figure 1: Vehicle trajectory (pivot turn)

Figure 2: Experimental situation of pivot turn.

deceleration as the collision progresses. On the other hand, since the rear wheel side is heavy in the used test car, the following ingenuity was made. The front wheels are set on a low μ road and the rear wheel are set on a high μ road as shown in Fig. 2. A positive force of each $180, 220$ N is applied to the front and rear right wheels and negative $180, 220$ N is applied to the front and rear left wheels. The experimental situation is shown on Fig. 2.

Fig. 3 shows the experimental result. Yaw rate is generated due to the differences between the driving force of left and right wheels. Owing to the bad condition of experimental vehicle, rear left wheel. However, yaw generation by different driving forces itself could be achieved. This can be said to be an experimental proof that an offset collided four wheel IWM car can change the vehicle direction and successfully reduce the collision force received. The "front" and "rear" in Fig. 3 followed the structure of the experimental vehicle.

4 Simulation

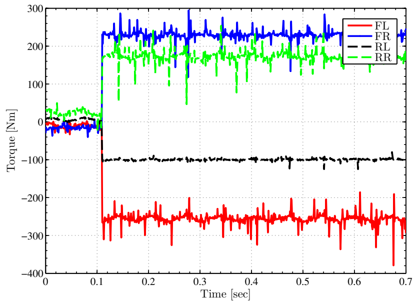
4.1 Simulation condition

A simulation study is conducted to verify the active collision damage reduction system. The vehicle parameters of the FPEV2-kanon are used for the simulation study again. The vehicle is assumed to be running at the speed of 10 m/s, and colliding on the wall of the spring model with 5cm offset as shown in Fig. 4. The wall was represented by a pole and we simulated the situation where the car stabbed into a strong pole. Here, x_w is the x coordinate of the wall, and the spring constant of the wall is assumed to be $k_w = 2 \times 10^4$ N / mm.

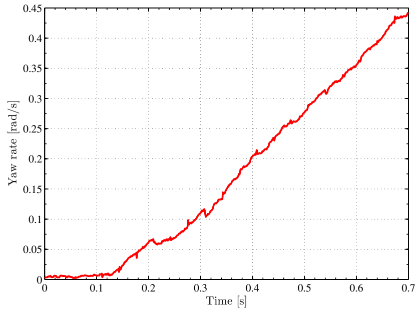
The collision force mitigation control starts at the timing when the vehicle reaches the coordinates at which the tip of it collides. For comparison, the following three cases were simulated and their collision forces are evaluated: without control (case 1), retracting vehicle with full power by four IWMs (case 2), and proposed collision damage reduction system (case 3). In case 3, the maximum torque is applied to the left and right wheels in the opposite direction so that the vehicle body rotates in the direction in which the impact is relaxed.

4.2 Simulation results

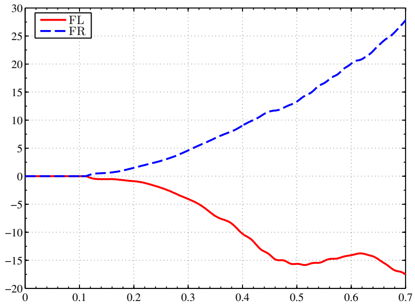
Simulation results are shown in Fig. 5 - 12. The simulation time is 400 ms around the collision, Fig. 6 plots the vehicle attitude every 40 ms, and the wall is represented by black dots. From Fig. 5, the magnitude of the collision force is case 1 $>$ case 2 $>$ case 3. In either case, the vehicle rotates by the



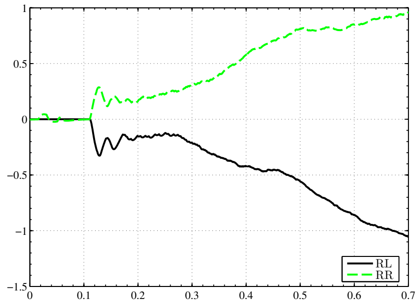
(a) Input torque.



(b) Yaw rate.



(c) Angular velocity of front wheel.



(d) Angular velocity of rear wheel.

Figure 3: Pivot turn of IWM-EV (experiment).

action of external force during the collision, and the impact forces abruptly become zero at the departure point. In case 1, most of the momentum of the vehicle is used for the collision and the large collision force has occurred. In case 2, collision force is reduced by dissipating a part of the momentum of the vehicle by the brake. On the other hand, in case 3, the vehicle is rotated smoothly by the action of the different driving force of the IWMs and the external force, and the collision point is shifted early.

Case 3 has the greatest collision mitigation effect, because the collision point is shifted and the collision force becomes 0 at the earliest. In case 3, the collision force was reduced by 8 % compared with case 1. Although there was no dramatic improvement, the proposed method was slightly effective.

Also, as a result of simulation with various patterns by assigning a plurality the initial speeds, it was found that the effectiveness of "ukemi" control becomes greater as the speed becomes lower.

4.3 Consideration

In this section, we describe collision mitigation by passive passenger when vehicle collides with offset. For the sake of simplicity, the rear wheels are floating here, they do not generate driving force, and the driving force of the wheels is represented by the ratio of the input torque of the wheels to the radius. Since the dominant collision force acting on the vehicle is in the x-axis direction, when the rotation angle of the vehicle reaches 90 ° during the collision, the collision force can be completely passed through in the rotation direction.

When a turning force around the center of gravity of τ acts on the vehicle, we get (1) about the attitude angle θ of the vehicle by second-order integration of the rotational motion equation in the yaw direction of the vehicle.

$$\theta = \frac{\tau}{2I}t^2 \tag{1}$$

From (1), the yaw moment necessary to rotate the body angle 90 ° during the collision 100 ms is given by (2).

$$\tau_{req} = \frac{I\pi}{0.01} \tag{2}$$

Here, when torque inputs of T_f and $-T_f$ are applied to each of the left and right wheels, the moment that can be created by the driving force difference of the wheel is the following.

$$\tau_{tire} = 2\frac{T}{r}\frac{d}{2} = \frac{2T_f}{r} \tag{3}$$

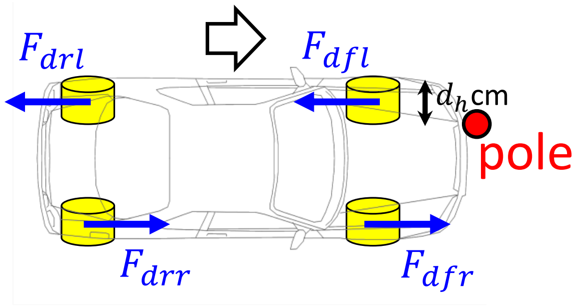
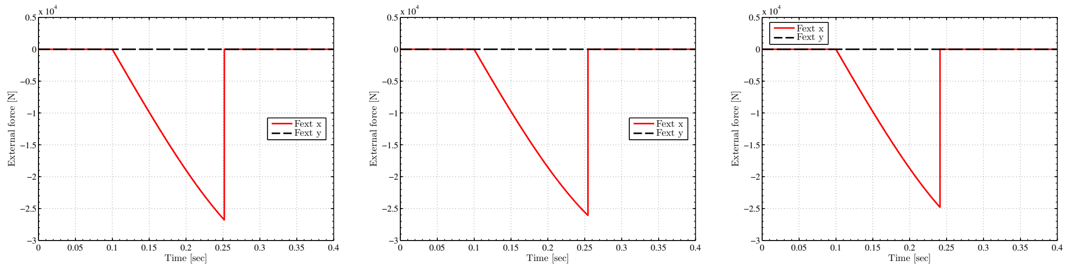


Figure 4: Simulation situation.



(a) without control (b) with control (c) with rolling control

Figure 5: Collision force

Computing the torque required for each wheel of the front wheel is equal to

$$T = 50\pi r I = 29269\text{Nm} \tag{4}$$

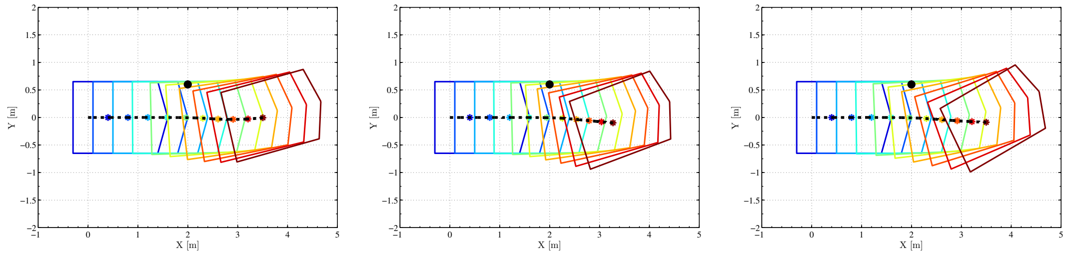
The maximum torque input of all the experimental vehicle rear wheels is $625Nm$, which is much smaller than the required torque, so the effect of the simulation to reduce the collision force is only about a few $\%$
On the other hand, as shown in (1), since the required torque decreases in proportion to the square of the time. There is a possibility that better results can be obtained by starting the proposed control from a point before the collision.

5 Conclusion

We proposed a method to mitigate accident damage actively using IWM-EVs. Moreover, its effectiveness is shown by preliminary experiment and simulation.
Through simulation studies, it was shown that the proposed method is effective but it is difficult to relieve dramatic collision by proposed method in the current FPEV 2-kanon vehicle specification. Therefore, control will be added from a time earlier than the collision, and a method to reduce the collision force by combining braking and passive will be studied.
Also, in this simulation, active collision mitigation control was performed by inputting the maximum torque of each wheel also as confirmation of the behavior of the simulator. However, since the actual wheel slips, the maximum driving force is not exerted in the simulation. Therefore, in the next step, we will study the case where maximum driving force is always generated for each wheel while preventing saturation of driving force by slip by using driving force control [7] etc.

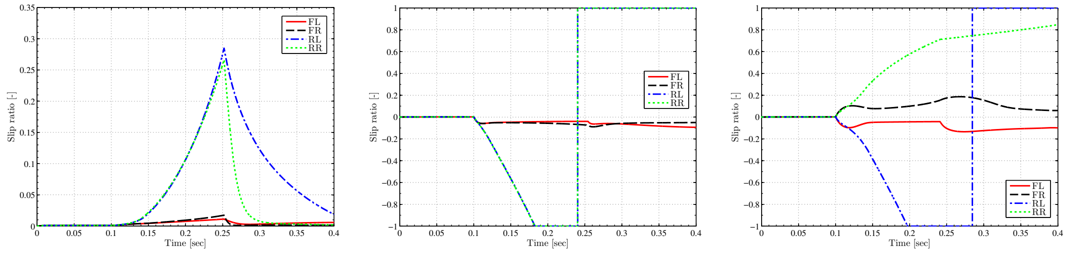
Acknowledgments

We express our sincere thanks to Mr. Nakano and Mr. Murakami of Nissan MOTORs, CO., Ltd. Advice and comments given by them has been a great help in the launch of this research. This research is partly supported by Industrial Technology Research Grant Program from New Energy and Industrial Technology Development Organization (NEDO) of Japan (number 05A48701d), the Ministry of Education, Culture, Sports, Science and Technology grant (number 22246057 and 26249061).



(a) without control (b) with control (c) with rolling control

Figure 6: Vehicle trajectory



(a) without control (b) with control (c) with rolling control

Figure 7: Slip ratio

References

[1] E. Egea-lopez and J. Garcia-haro, “Vehicular Trajectory Optimization for Cooperative Collision Avoidance at High Speeds,” IEEE Trans. Intell. Transp. Syst., vol. 14, no. 4, pp. 1930-1941, 2013.

[2] C. Choi, Y. Kang, and S. Lee, “Emergency Collision Avoidance Maneuver based on Nonlinear Model Predictive Control,” in International Conference on Vehicular Electronics and Safety, 2012, pp. 393-398.

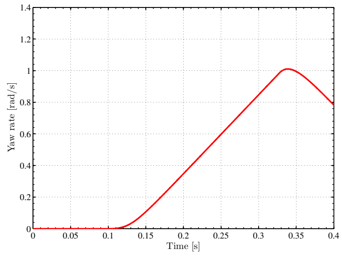
[3] N. Shimoya and H. Fujimoto, “Fundamental Study of Driving Force Distribution Method for Minimization of Maximum Slip Ratio for Electric Vehicles with In-wheel Motors,” in International Electric Vehicle Technology Conference & Automotive Power Electronics Japan, EVTeC2016, 2016.

[4] J. Marzbanrad, M. Alijanpour, and M. S. Kiasat, “Design and analysis of an automotive bumper beam in low-speed frontal crashes,” Thin-Walled Struct., vol. 47, no. 8-9, pp. 902911, 2009.

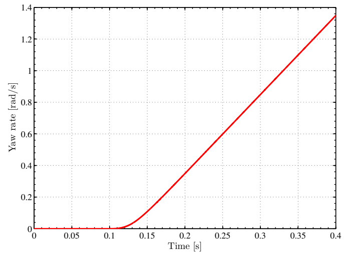
[5] S. Murata, “Innovation by in-wheel-motor drive unit,” Veh. Syst. Dyn., vol. 50, no. 6, pp. 807830, 2012.

[6] F. Cedex, G. Campion, and G. Bastin, “Control of Nonholonomic Wheeled Mobile Robots by State Feedback Linearization,” pp. 543-559.

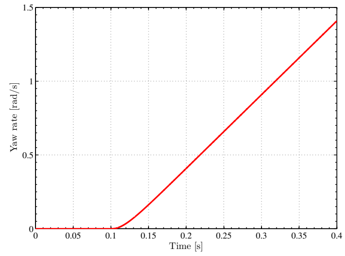
[7] M. Yoshimura and H. Fujimoto, “Driving Torque Control Method for Electric Vehicle with In-Wheel Motors,” IEEJ Trans. Ind. Appl., vol. 181, no. 3, pp. 721-728, 2012.



(a) without control

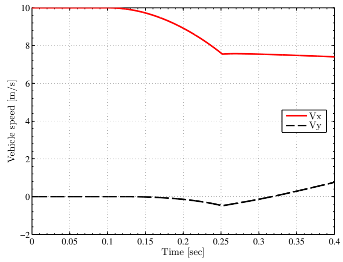


(b) with control

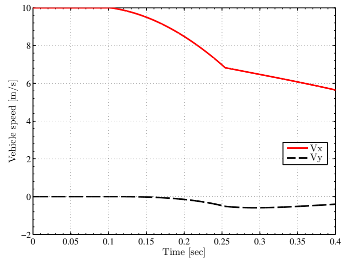


(c) with rolling control

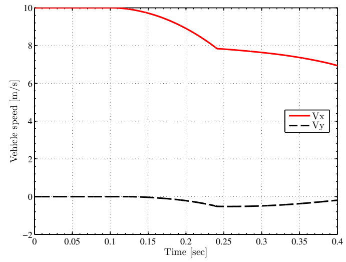
Figure 8: Yaw rate



(a) without control



(b) with control



(c) with rolling control

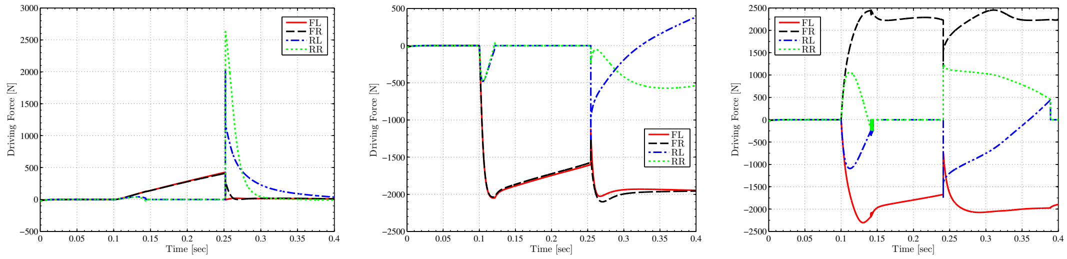
Figure 9: Vehicle speed

Authors

Tomoki Enmei is a doctor course student of department of electrical engineering, in the Graduate School of Engineering at the University of Tokyo, Japan. He graduated the Bachelor course in electrical and electronic engineering in 2015 and Master course in advanced energy at the University of Tokyo in 2017. His research interests include motion control, Electric Vehicles (EVs), force control of industrial robots, and high speed force curve measurement control for atomic force microscopy (AFM). He is a member of the Institute of Electrical Engineers of Japan.

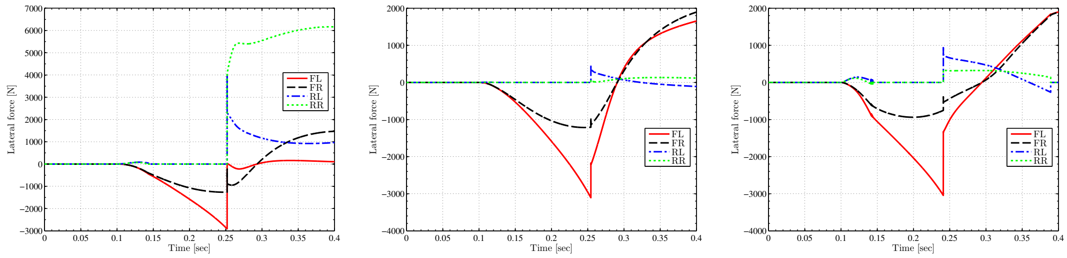
Dr. Hiroshi Fujimoto received the Ph.D. degree in the Department of Electrical Engineering from the University of Tokyo in 2001. He is currently an associate professor of the University of Tokyo since 2010. He received the Best Paper Award from the IEEE Transactions on Industrial Electronics in 2001 and 2013, Isao Takahashi Power Electronics Award in 2010, and Best Author Prize of SICE in 2010. His interests are in motion control, nano-scale servo systems, electric vehicle control, and motor drive. Dr. Fujimoto is a member of IEEE, the Society of Instrument and Control Engineers, the Robotics Society of Japan, and the Society of Automotive Engineers of Japan.

Dr. Yoichi Hori received his Ph.D. in electrical engineering from The University of Tokyo, Japan, 1983, where he became a Professor in 2000. In 2008, he moved to the Department of Advanced Energy, Graduate School of Frontier Sciences. Prof. Hori was the recipient of the Best Paper Award from the IEEE Transactions on Industrial Electronics in 1993, 2001 and 2013 and of the 2000 Best Paper Award from the Institute of Electrical Engineers of Japan (IEEJ). He is the Chairman of the Motor Technology Symposium of the Japan Management Association.



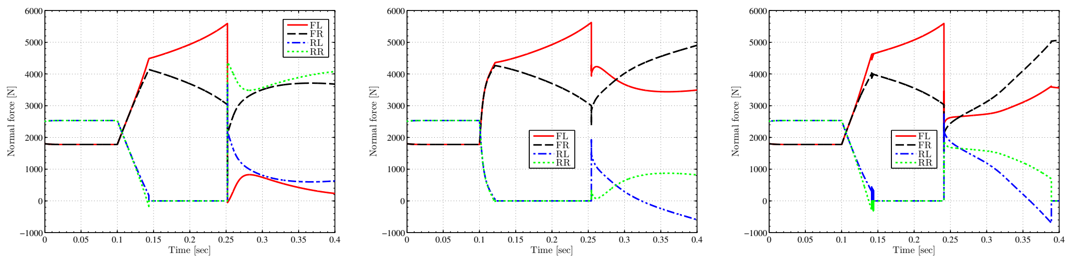
(a) without control (b) with control (c) with rolling control

Figure 10: Tire longitudinal force



(a) without control (b) with control (c) with rolling control

Figure 11: Tire lateral force



(a) without control (b) with control (c) with rolling control

Figure 12: Tire normal force