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A New Force Feedback for Steer-by-Wire Vehicles via Virtual Vehicle Concept

Emad Mehdizadeh, Mansour Kabganian, and Reza Kazemi

Abstract— **Creating reasonable steering feel is an underlying issue in Steer-by-Wire (SbW) vehicles especially when a lanekeeping assistance system functions along with the driver. In order for the artificial force feedback to be familiar to driver, as it is shown in this paper, it must not be built based upon the real roadwheels reaction torque simply because this torque could involve the contribution of lanekeeping controller. If this contribution is fed back to driver, they might perceive the force feedback as unnatural behavior and provoke unanticipated rushed reactions which may, in turn, destabilize the car. As opposed to current methods, that seek to estimate the real reaction torque at the roadwheels, a reference model as the virtual vehicle is employed here to produce a force feedback that corresponds closely to conventional steering systems. Not only does the new force feedback feel like a conventional system which is indeed familiar to the driver, it improves performance of lanekeeping system in comparison with current methods and actually gives the maximum performance as if there is no force feedback system. Simulations are carried out to evaluate the performance of current and proposed force feedback systems.**

I. Introduction

SBW technology by omitting the intermediate shaft, available in conventional vehicles, allows the possibility of independently commanding the roadwheels through both driver and lanekeeping assistance system. When the lanekeeping system works along with the driver, the steering wheel angle would differ from that of the roadwheels. The difference between steering wheel and roadwheel angles makes it a complex task to create familiar steering feel for driver since the lanekeeping controller input could contribute to the roadwheels reaction torque which is the source of steering feel in conventional steering systems.

Despite the large number of papers in the literature, none of them have taken the effect of this difference into account to create a reasonable steering feel. The existing research on producing artificial force feedback has attempted to obtain the real roadwheels reaction torque through various methods. Assuming a generic power steering system as the desired dynamics, Odenthal *et al.* [1] tried to supply an adequate feeling of the actual tire forces to the driver by applying a model matching approach. Seflur *et al.* [2] presented a nonlinear tracking controller that provided the driver with tunable force feedback, proportional to the reaction torque at the tire-rode interface. Im *et al.* [3] utilized a disturbance observer to estimate real reactive torque of the roadwheels. Nguyen and Ryu [4] proposed a method to directly measure the roadwheel reaction torque through a current sensor the rack steering mechanism. The steering feel produced by these methods can be unfamiliar to driver in many situations as they involve the influence of assistance system over and above the driver. Furthermore, the existing methods make vehicle-steering wheel dynamics a complex and coupled system which necessitates dealing with the problem of the combined system stability. To clarify this issue, suppose that the driver's hands are off the wheel; keeping in mind that steering wheel angle is zero, when the lanekeeping controller steers the vehicle, a reaction torque at roadwheels will be created. If this reaction torque is fed back to the steering wheel, makes it move in response to mere force feedback which is basically impossible in conventional steering systems. This movement starts, in turn, to steer the vehicle in parallel with the lanekeeping controller and this creates a coupled system which necessitates dealing with stability of the coupled system. In regard to this issue, Switkes *et al.* [5] obtained a mathematical model for the real reaction torque to redesign parameters of the combined system including lanekeeping controller and force feedback system parameters. To achieve stability in the presence of this force feedback system, they added an extra term to the roadwheel reaction torque, based on the level of lanekeeping assistance being given, which itself is another source of unfamiliarity.

Based upon the concept of a virtual vehicle, a new force feedback is designed so as to exclude the effect of lanekeeping controller input and makes the driver feel the very same as a conventional steering system. Also, this approach improves the lanekeeping system performance by decoupling the vehicle and steering wheel dynamics for which there would be no more need for stability consideration of the combined lanekeeping and force feedback systems.

II. Vehicle Modeling

A bicycle model (Fig. 1) is used as the reference model for the virtual vehicle. Using Newton's second law the equations of motion for the front-wheel drive vehicle are obtained as follows [6]

$$\ddot{x} = \dot{y}\dot{\theta} + \frac{1}{m}\big[(F_{xfl}+F_{xfr})\cos\delta - (F_{yfl}+F_{yfr})\sin\delta + F_{xrl}+F_{xrr}\big] \tag{1}$$

$$\ddot{y} = -\dot{x}\dot{\theta} + \frac{1}{m}\big[(F_{xfl}+F_{xfr})\sin\delta + (F_{yfl}+F_{yfr})\cos\delta + F_{yrl}+F_{yrr}\big] \tag{2}$$

$$\ddot{\theta} = \frac{1}{I_z}\Big[L_f(F_{xfl}+F_{xfr})\sin\delta + L_f(F_{yfl}+F_{yfr})\cos\delta - L_r(F_{yrl}+F_{yrr}) - \frac{T_f}{2}(F_{xfl}-F_{xfr})\cos\delta + \frac{T_f}{2}(F_{yfl}-F_{yfr})\sin\delta - \frac{T_r}{2}(F_{xrl}-F_{xrr})\Big] \tag{3}$$

E. Mehdizadeh and M. Kabganian are with System Dynamics and Control Research Laboratory, Department of Mechanical Engineering, Amirkabir University of Technology, Tehran 15914, Iran (e-mail: emehdizadeh@aut.ac.ir; kabgan@aut.ac.ir).

R. Kazemi is with the Department of Mechanical Engineering, K. N. Toosi University of Technology, Tehran 19697, Iran (e-mail: kazemi@kntu.ac.ir).

where m and I_z are the vehicle mass and inertia, respectively.

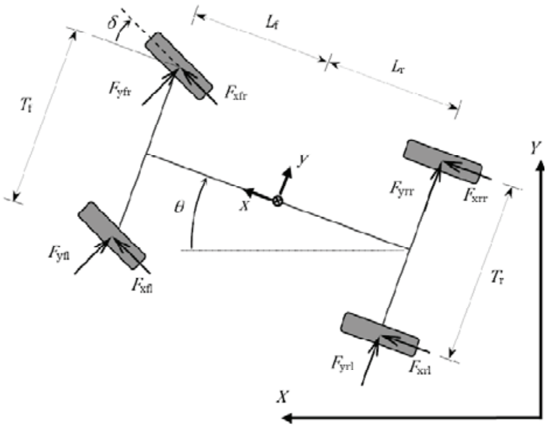


Fig. 1. Three DOFs plane vehicle model.

These equations are obtained assuming the zero aerodynamic side force. Since these equations are to be implemented in real-time simulations they should be simplified. Assuming zero resultant longitudinal forces, constant longitudinal velocity, small roadwheel angle and equal left and right slip angles, equations (1) to (3) reduce to [7]

$$\ddot{y} = -\frac{1}{mv_x}\left(C_f + C_r\right)\dot{y} - \frac{1}{mv_x}\left(L_f C_f + L_r C_r\right)\dot{\theta} - v_x\dot{\theta} + \frac{C_f}{m}\delta \tag{4}$$

$$\ddot{\theta} = -\frac{1}{I_z v_x}\left({L_f}^2 C_f + {L_r}^2 C_r\right)\dot{\theta} - \frac{1}{I_z v_x}\left(L_f C_f - L_r C_r\right)\dot{y} + \frac{L_f C_f}{m}\delta \tag{5}$$

in which the linear tire models, shown below, are employed.

$$F_{yf} = C_f \alpha_f = C_f(\delta - \frac{\dot{y} + L_f\dot{\theta}}{v_x}) \tag{6}$$

$$F_{yr} = C_r \alpha_r = C_r(-\frac{\dot{y} - L_r\dot{\theta}}{v_x}) \tag{7}$$

where v_x is the vehicle longitudinal velocity and C_f and C_r are the front and rear cornering stiffnesses, respectively.

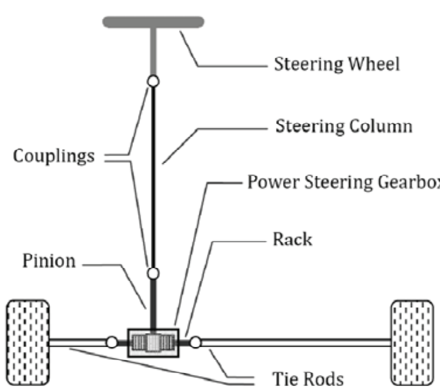


Fig. 2. Schematic of a conventional steering system.

III. Steering Wheel Modeling

To design an appropriate force feedback for the SbW system, it is required to carefully investigate the vehicle steering system.

A. Conventional Steering System

Schematic of a conventional steering system is depicted in Fig. 2. To model the conventional steering system, the resulting torque from friction effect is neglected with respect to the reaction torque at the roadwheels. Also the stiffness of steering system components assumed to be infinite. Thus the equation of motion for the steering wheel is expressed as

$$\ddot{\varphi} = \frac{1}{(I_{sw} + I_{sc})}[-b_{ps}\dot{\varphi} - \left(\frac{1}{N_{sg}}\right)\tau_r + \tau_d] \tag{8}$$

where I_{sw} and I_{sc} are the inertia of the steering wheel and steering column, respectively, b_{ps} the viscous damping coefficient of the power steering system, φ steering wheel angle, N_{sg} overall steering ratio, τ_r reaction torque of the roadwheels, and τ_d input torque of driver.

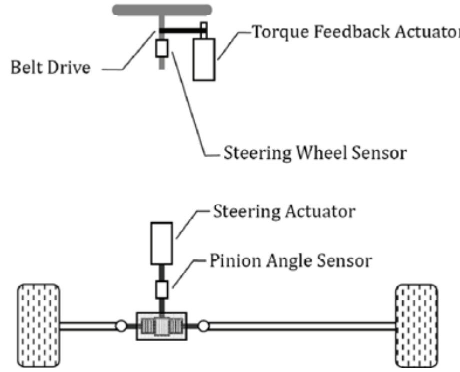


Fig. 3. Schematic of a conventional steering system.

B. Steer-by-Wire System

A Steer by Wire system, for which the steering column is removed, offers the possibility of vehicle active lateral control through the fact that both driver and lanekeeping system would be separately capable of commanding the steering system. Instead two actuators (see Fig. 3) must be installed in the steering system to serve the functions of the steering column; one for recreating the driver steering feel and the other for tracking the total steering angle obtained from the driver and lanekeeping system inputs. Here, the focus is on the driver steering feel and as a result only the steering wheel model is presented. The SbW steering wheel, neglecting viscous damping and coulomb friction, can be modeled as

$$\ddot{\varphi} = \frac{1}{I_{sw}}(\tau_m + \tau_d) \tag{9}$$

where τ_m is the force feedback applied by the motor.

C. Roadwheels Reaction Torque

The important elements of a steering system consist not only of the visible linkages, but also the geometry associated with the steer rotation axis (kingpin axis) at the roadwheel. This geometry determines the moment reactions of the roadwheels to the driver [8]. The important features of the geometry are depicted in Fig. 4.

The steer rotation axis is normally not vertical, but may be tipped outward at the bottom, producing a lateral inclination angle λ. Caster angle υ results when the steer rotation axis is inclined in the longitudinal plane. Positive caster aids in centering the steering wheel after a turn and makes the front tires straighten quicker [9]. Positive inclination and caster angles are shown in the figure.

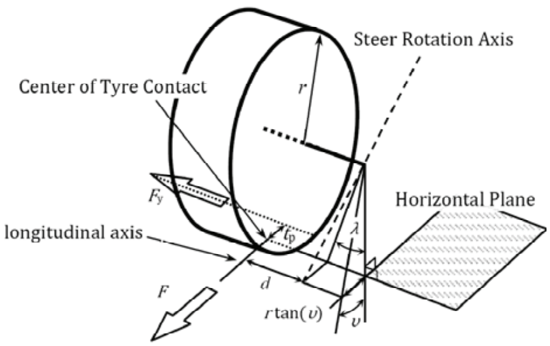


Fig. 4. Schematic of a SbW system.

The distance of tire longitudinal axis from steer rotation axis when intersects the ground is called lateral offset d which provides feel of the road and reduces static steering efforts by allowing the tire to roll around an arc when it is turned [10]. Due to nonsymmetrical stress distribution on the tires, the resultant force does not usually act at the center of tire contact, but within some distance in tire contact area. The distance between center of tire contact and resultant lateral force is called the pneumatic trail t_p.

Assuming the longitudinal force to be zero after setting the origin of tire coordinate frame at the center of tire contact and measuring all tire-road reactions in this frame, the significant sources for reaction torque would be aligning torque, lateral and vertical forces [8].

1) Aligning Torque: The resultant lateral force, which is acting at a distance t_p behind the center of tire contact, may be replaced with a lateral force at the origin and a vertical moment called aligning torque. Aligning torque tends to make the tire align with the direction of tire velocity vector and may be resolved into a component acting parallel to the steering axis. The net moment for the right and left tires is

$$\tau_a = t_p(F_{yfl} + F_{yfr}) \tag{10}$$

2) Lateral Force: The lateral force acting at the center of tire contact produces a moment through the longitudinal offset resulting from caster angle. The net moment produced is

$$\tau_l = r \tan \upsilon \ (F_{yfl} + F_{yfr}) \tag{11}$$

3) Normal Force: Since the steering axis is inclined, the front normal force F_{zf} has a component acting to produce a moment tending to steer the wheel. Assuming the angles to be small and neglecting camber angle, the angle of the tire relative to the vertical line, the total moment from left and right tires can be approximated by

$$\begin{aligned} \tau_n = & (F_{zfl} + F_{zfr}) d \sin \lambda \sin \delta \\ & + (F_{zfl} - F_{zfr}) d \sin \upsilon \cos \delta \end{aligned} \tag{12}$$

Where, the first expression on the right side arises from lateral inclination angle and the last from caster angle. For the latter term, the moments on the left and right tires are opposite in direction and tend to balance each other.

Ultimately, the sum of these moments produced on the steer axis accounts for the roadwheel reaction torque which is

$$\tau_r = (t_p + r \tan \upsilon) \cos \sqrt{\lambda^2 + \upsilon^2}\, F_{yf} + d \sin \lambda \sin \delta\, F_{zf} \tag{13}$$

This torque, lessened through the steering ratio, must be resisted to control the steering wheel angle.

IV. Force Feedback Controller Design

In order for the force feedback to function like a conventional steering system it must be designed so as to match the dynamic model of the SbW steering system with that of the conventional system. This can be done by subtracting equation (8) from (9). After substituting the linear front tire model (equation (6)), the designed steering force feedback, assuming small steering angle, is obtained as follows

$$\tau_m = -I_{sc}\ddot{\varphi} - b_{ps}\dot{\varphi} + k_1\left(\frac{1}{v_x}\dot{y} + \frac{L_f}{v_x}\dot{\theta} - \delta\right) - k_2\delta \tag{14.a}$$

where k_1 and k_2 are

$$k_1 = \frac{1}{N_{sg}}(t_p + r \tan \upsilon) \cos \sqrt{\lambda^2 + \upsilon^2} C_f \tag{14.b}$$

$$k_2 = \frac{1}{N_{sg}}(d \sin \lambda\, F_{zf}) \tag{14.c}$$

The design procedure is not complete yet. In addition to precise development of the mathematical expression, it is also required to carefully determine each parameter/state value to guarantee the familiarity of steering feel.

TABLE I
PARAMETERS OF THE STEERING TORQUE FEEDBACK DESIGN

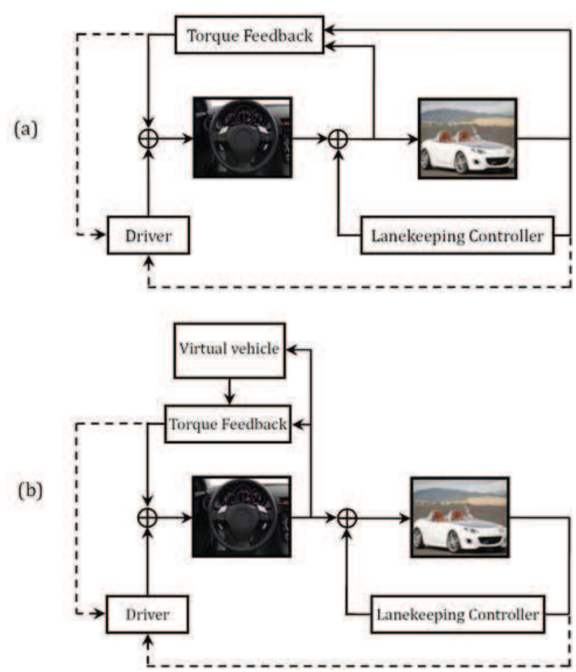
Parameters	Design Values Range	Units
I_{sc}	0.004-0.02	kg m^2
b_{ps}	1-10	Nms/rad
k_1	120-495	Nm/rad
k_2	2-9	Nm/rad
L_f	1.22-1.3	m
v_x	Online Measured	m/s

A. Parameters Values

In order to create a reasonable steering feel, the values of parameters should be chosen physically rather than from stability perspective as it is done in [5]. Although in terms of different cars parameters values may vary, all of them are within a typical range. Most passenger cars are made with 4-6 deg caster angle [9], 10-15 deg inclination angle, 15-20 steering ratio, 20-30 mm lateral offset [8] and 20-25 mm pneumatic trail [11]. Moreover, 280-350 mm for tire radius, 1300-1800 kg for vehicle mass and 30-120 kN/rad for tire cornering stiffness cover a wide range of today's passenger cars and road conditions. According to the typical values, the range of design parameters is adopted as shown in Table 1.

B. States Values

The values of vehicle states influencing the force feedback should also be carefully determined. The state values are directly related to the roadwheel angle which is basically different in conventional and SbW systems. In a conventional steering system, the roadwheel angle is directly related to steering wheel angle through the steering ratio. Whereas in a SbW system there is no more such relationship since an additional input from the lanekeeping assistant system can be added to the steering input of driver. In fact, in a SbW vehicle equipped with lanekeeping assistance system the tire angle differs from driver input. As drivers have been always expecting to feel a force feedback according to their own steering input, the actual reaction torque at the roadwheels of a SbW vehicle might seem unreasonable to them. Substituting the actual vehicle states, which include the effect of lanekeeping controller input, in (14) tends to replicate the actual roadwheels reaction torque. Instead, a virtual motion that characterizes the conventional steering systems can be generated through a reference model to only involve the influence of driver steering input. The concluding virtual states can be employed to create a new unrealistic force feedback which is akin to conventional steering systems.



1) Force Feedback Based on Actual Tires Reaction Torque: Using the actual reaction torque of the roadwheels as the artificial force feedback is problematic when a SbW vehicle is equipped with lanekeeping assistance system. In a SbW system, the steering wheel and lanekeeping system inputs add up to a total roadwheel angle; the contribution of this total angle would determine the roadwheel reaction torque. This reaction torque can be unfamiliar to driver since it involves the influence of lanekeeping controller input about which the driver has no idea. The previous works have tried to obtain the real reaction torque of roadwheels to create artificial force feedback. The signal block diagram in Fig. 5(a) shows that how the current methods make use of real vehicle states to create a force feedback at the steering wheel. For this method, even with zero driver steering input, the value of artificial force feedback can be nonzero because having an input from the lanekeeping system suffices to create a reaction torque at the roadwheels. This behavior, which is fundamentally abnormal, is a clear-cut proof of why this kind of approach cannot be natural for drivers because they do not expect to feel a reaction torque unless they themselves apply a steering input. Not only does such force feedback seem unfamiliar to driver in many situations, it can diminish the performance of lanekeeping task significantly. When driver is not in charge of the driving task, the lanekeeping system solely takes steering control of the vehicle. Unexpectedly, despite the zero input of the steering wheel, it would eventually moves as a result of this kind of artificial force feedback. Such unnecessary movement of the steering wheel is disadvantageous and can destabilize the car if not handled properly. Switkes et al. [9] tried to prevent instability by adding an extra term 'lanekeeping assistance force' to the force feedback expression and redesigning the parameters of the combined system (force feedback and lanekeeping controller parameters). The new set of parameters could eventually provide vehicle stability. However the extra term 'lanekeeping assistance force' added another source of unfamiliarity to driver as well as the already discussed source. This change in performance will be shown in the results and discussion section. Here, the mathematical expression of the conventional approach [5] is formulated

$$\tau_m = -I_{sc}\ddot{\varphi} - b_{ps}\dot{\varphi} + k_1\left(\frac{\dot{Y}}{v_x} - \theta + \frac{\dot{\theta}L_f}{v_x} - \frac{\varphi}{N_{sg}} - \delta_c\right) - k_2\left(\frac{\varphi}{N_{sg}} + \delta_c\right) + k_{pf}C_f\delta_c \tag{15}$$

This equation is expressed in road-fixed coordinates. The final term shows the extra term aimed at stabilizing the vehicle.

2) Unrealistic Force Feedback Based upon a Virtual Vehicle: To have a more proper feel, instead of accurate prediction of the SbW roadwheels reaction torque, force feedback should bear a resemblance to the reaction torque of conventional steering system. Thus, it must be designed so as to be only influenced by the driver's steering input. In the proposed method the controller steering input does not have any effect on the force feedback (Fig. 5(b)). Instead, the states present in force feedback controller are obtained through a reference model as a virtual conventional vehicle. Driver's steering input which is measured by a sensor, installed at the steering wheel, is applied to the reference model to create a virtual motion similar to the conventional steering. The set of obtained virtual states can be used to make artificial force feedback. Although, the new force feedback does not predict the roadwheels reaction torque it would make driver feels as if they are driving with a conventional vehicle. Utilizing this method the steering wheel would be unmoved as long as driver does contribute in steering task. There is also no more need for redesigning force feedback and lanekeeping controller parameters for preventing vehicle instability as in this approach the steering wheel and vehicle dynamics are decoupled (as can be seen in Fig. 5(b)).

Since the reference model must be experimentally implemented, in addition to accuracy it must be simple enough to be applicable in real-time simulation. As a result, linear equations (4) and (5) are employed as the reference model. Although not very accurate for non-highway usage, this model suffices the need for providing driver with a reasonable feel. Substituting the steering wheel angle and virtual vehicle states for roadwheel angle and vehicle states respectively, in equation (14.a), the new force feedback controller would be obtained as

$$\tau_m = -I_{sc}\ddot{\varphi} - b_{ps}\dot{\varphi} + k_1\left(\frac{\dot{y}'}{v_x} - \theta + \frac{\dot{\theta}' L_f}{v_x} - \frac{\varphi}{N_{sg}}\right) - k_2\frac{\varphi}{N_{sg}} \tag{16}$$

This equation is expressed in vehicle-fixed coordinates. The prime superscript stands for the virtual states obtained through the reference model.

V. Lanekeeping Assistance System

In order to examine the performance of the two force feedback systems, the potential field lanekeeping controller introduced by Rossetter and Gerdes [12] is employed here. This controller makes use of lateral and heading error to keep the vehicle in the lane. The steering angle based on the potential field controller is:

$$\delta_c = \frac{2k_p(Y + d_{la}\theta)}{C_f} \tag{17}$$

where k_p and d_{la} are the potential field coefficient and look-ahead distance, respectively.

TABLE II
Vehicle and Steering System Parameters

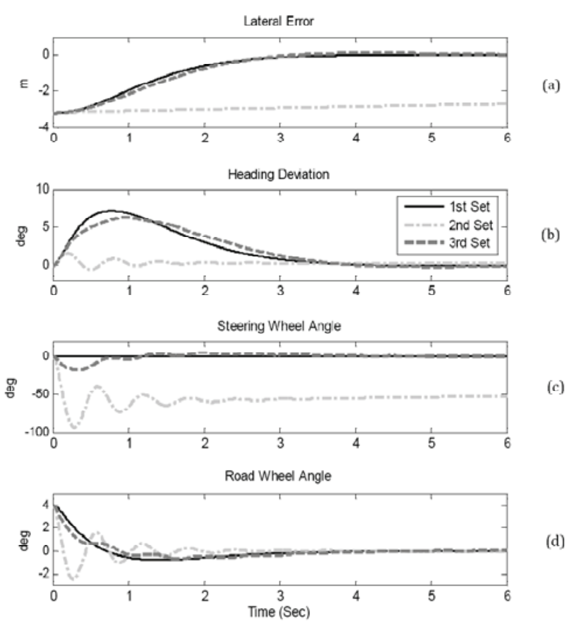
Parameters	Values	Units
I_z	2500	kg m^2
m	1470	kg
C_f	110,000	N/rad
C_r	100,000	N/rad
L_f	1.3	m
L_r	1.3	m
N_{sg}	16	—
I_{sw}	0.084	kg m^2

VI. Results and Discussion

First it is demonstrated that the existing force feedback methods diminish the performance of lanekeeping assistance system. For this purpose, a recent work carried out by Switkes *et al.* [5], which considers the influence of force feedback working along with a lanekeeping system, is designated. Then the performance of the lanekeeping assistance system in the presence of the new force feedback approach is evaluated. To preserve consistency in simulations, for both works it is assumed that driver does not contribute in driving task. The initial steering wheel position is also considered to be zero. Table 2 shows the vehicle parameters used in the simulations.

Four sets of parameters for evaluating the existing force feedback approach have been chosen (Table 3). Employing the first set (equivalent to the fifth set in some manner) would determine the lanekeeping system performance in the absence of any force feedback system. The second and third sets, which are taken from [5], stand for parameters of the existing force feedback approach without and with the extra term 'lanekeeping assistance force', respectively. As it can be seen, not all of the parameters of these two sets are within the design value ranges (depicted in Table 1) for which the steering feel is familiar to the driver. The fourth set which is approximately chosen at the midpoint of design value ranges, assuming K_{pf} to be zero, is duplicated to the sixth set to compare the performance of current approach with the new one. By this comparison it is aimed to show that when the parameters of force feedback are designated within the physical quantities the new system performs much better than the current method, without requiring any additional term that can make unfamiliarity to driver.

After applying the first three sets (existing force feedback method) into the simulation the system performance is illustrated in Fig. 6. As it can be seen without the term of lanekeeping assistance force ($K_{pf} = 0$) the system performance is highly unsatisfactory but adding this term in the third set the system performance improves but still is slightly deviated from the desired performance (solid line). This force feedback system also creates a torque that moves the steering wheel when it is released from the neutral point (Fig. 6(c)). This movement clearly demonstrates that the current force feedback methods tend to interfere in driving task. Such movement, as discussed in the previous sections, is not only useless but also disadvantageous in two ways, it is fundamentally an abnormal behavior which is unfamiliar to driver and meanwhile makes the steering wheel and vehicle systems coupled.

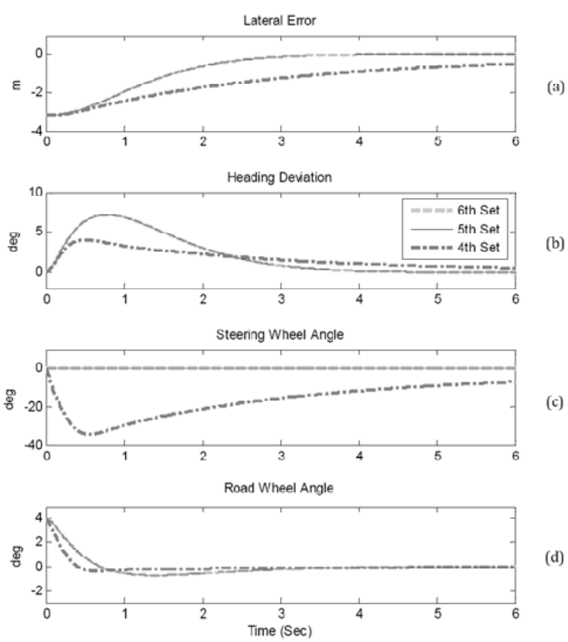


Comparing the second and third sets, it can be seen that with small changes in parameters the amount of roadwheel movement considerably changes which can even destabilize the vehicle.

To compare the performance of system in the presence of new and existing force feedback systems, the fourth, fifth and sixth sets of parameters are used to carry out the simulation again. The simulation results for the three sets (Fig. 7) show that the performance of new force feedback exactly matches the desired one (solid line, when there is no force feedback), and obviously it gives better results with respect to the existing approaches. It can be also seen from (Fig. 7(c)) that the steering wheel maintains unmoved as the lanekeeping system functions.

TABLE III
VEHICLE AND STEERING SYSTEM PARAMETERS

Parameters	Existing Force Feedback (FF) Method				New FF Method		Units
	1st Set	2nd Set	3rd Set	4th Set	5th Set	6th Set	
I_{sc}	0	0.009	0.009	0.01	0	0.01	kg m^2
b_{ps}	0	0.208	0.208	3	0	3	Nms/rad
k_1	0	200	200	300	0	300	Nm/rad
k_2	0	45	45	5	0	5	Nm/rad
k_{pf}	0	0	143	0	—	—	Nm/kN
k_p	1750	1750	1750	1750	1750	1750	Nm/rad
d_{la}	20	20	20	20	20	20	Nm/kN



It can be seen from Fig. 7 that the new force feedback method does not interfere in driving task and so merely brings back the steering feel. As a result with any modification in the force feedback parameters there would be no change in the lanekeeping task result. These results were already predictable from Fig. 5 since the new system decoupled the lanekeeping and force feedback loops. This is exactly what happens for conventional steering systems for which without driver's steering input the steering wheel does not rotate.

VII. CONCLUSIONS

A novel approach for making force feedback was proposed which made use of virtual vehicle states through a linear vehicle model as the reference model. In fact, a virtual motion was achieved by applying the mere driver steering input to the reference model to duplicate conventional steering conditions. Although the new force feedback does not estimate the real reaction torque at the roadwheels, it can provide a familiar steering feel like a conventional steering system. The new approach is an effective and simple way in online applications and yet improves lanekeeping performance. Rather than current methods that can destabilize the vehicle for a wide range of force feedback parameters values, the new method decouples the vehicle and steering wheel systems and hence resolves any stability issue. The simulation results confirm that, as opposed to existing methods, the proposed force feedback system does not diminish the performance of lanekeeping assistance system.

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