INTRODUCTION

The Driver-Vehicle Dynamics Group at Cambridge University Engineering Department [1] develops driver models with the aim of shifting vehicle development activity to the low-cost design phase. Of special interest in the present paper is understanding the way in which the neuromuscular system (NMS) and steering torque feedback affect the response of the vehicle to external lateral force disturbances. Recent work by others on driver models incorporating the NMS includes that of Pick and Cole [2], Sentouh et al [3], Droogendijk [4] and Katzourakis et al [5]. The present paper extends the driver model of Pick and Cole [2] with an improved model of intrinsic muscle dynamics developed recently by Hoult [6]. He found that the intrinsic muscle dynamics are dominated by a damping term at low frequency, whereas previous studies [2,4,5] have employed models in which low frequency behaviour is dominated by a stiffness term. Improvements are also made to modelling of the cognitive delay and the alpha-gamma co-activation; in particular, the inverse model used in [2,4,5] to generate the co-activation signal is replaced by a forward model. The next section of the paper describes the vehicle and driver models. The open-loop response of the driver-vehicle system is examined in Section 3. Closed-loop path-following control is introduced in Section 4 and the effect of the driver's NMS on the vehicle response to lateral force disturbance is studied. Conclusions and recommendations for further work are given in the final section of the paper. A more complete description of the work, including experiment results, is given in [7], on which the present paper is based.

2. DRIVER-VEHICLE MODEL

The structure of the driver-vehicle model is shown in Figure 1. The model simulates path-following in the linear operating regime of the vehicle and at constant vehicle speed. Block $H_v$ is the vehicle, $H_s$ is the steering system, $H_m$ and $H_b$ are the muscle dynamics, and $H_r$ and $D_r$ are the muscle stretch reflex dynamics. These blocks comprise the system to be controlled by the driver's brain. The brain is represented by blocks $K$, $D_c$, and $H_f$, and generates the alpha and gamma control signals denoted by $\alpha$ and $\gamma$.

The vehicle ($H_v$) is represented using a linear lateral-yaw single-track vehicle model shown in Figure 2. All the parameters and their default values are given in [7]. The default values represent a passenger car with 50/50 mass distribution, unity dynamic index ($I=ma/b$) and neutral steer characteristic. The constant vehicle speed is $U$. The control input to the vehicle is the pinion angle $\theta$. The front road wheel steer angle $\delta$ is equal to the pinion angle $\theta$ divided by the steering gear ratio $G$. In addition to the tyre forces, external disturbance forces acting on the vehicle mass are lateral forces acting at the centre of mass ($F_g$), front axle position ($F_f$) and rear axle position ($F_r$) as shown in Figure 2. States are the lateral and yaw velocities $v$ and $\omega$ in vehicle-fixed axes.

For the purpose of calculating the lateral displacement of the vehicle relative to a ground-fixed axis it is assumed that the yaw angle $\psi$ of the vehicle relative to a ground-fixed axis remains small. The lateral displacement $y$ is then determined by integrating the lateral velocity $\dot{y} = v + U\dot{\psi}$. Pinion torque $T_p$ arises from the lateral front tyre force acting a distance $d$ behind the point where the kingpin axis intercepts the ground (mechanical plus pneumatic trail).

The muscle and steering model comprises the three blocks labelled $H_m$, $H_a$, and $H_b$. $H_a$ represents an unassisted mechanical steering system and the inertia of the driver's arms. The inertia of the steering system (comprising the handwheel, column, rack and pinion gear, front wheels and other steered components),
referenced to the pinion axis, is denoted by $I_r$. This inertia is connected to vehicle ground by a torsional stiffness $k_t$ that represents self-centring stiffness (typically arising from the weight of the vehicle acting through the suspension and steering geometry), and a parallel torsional damper $c_t$ to represent damping in the mechanism. The pinion torque $T_p$ (defined in the preceding subsection) arising from the lateral tyre force acts on the steering inertia. The inertia of the driver's arms referenced to the pinion axis is denoted $I_{arm}$ and is rigidly connected to the handwheel. The handwheel angle is assumed equal to the pinion angle. The arm muscles apply torque to the arm inertia. The muscle torque consists of two components, $T_b$ and $T_m$.

![Figure 1. Block diagram of driver-vehicle model.]()  

![Figure 2. Vehicle model with external disturbance forces acting at the centre of mass ($F_d$), front axle position ($F_f$) and rear axle position ($F_r$).]()

The muscle torque component $T_b$ arises from the internal stiffness and damping of the muscles and joints, known as the intrinsic torque. It is related to the handwheel angle $\theta$ by transfer function $H_b$. The transfer function is strongly dependent on the activation level of the muscle. Hoult [6] has identified this transfer function for a range of drivers with muscles tensed (co-contracted) and with muscles relaxed. The identified transfer function can be idealised as a linear viscous damper in parallel with a series-connected damper and spring. At low frequencies the damping terms dominate, and Hoult's measurements [6] indicate that the damping coefficients increase when the muscles are tensed (co-contracted). This can be ascribed to a greater number of cross-links being made in the muscle fibres when the muscle is activated strongly.

The muscle torque component $T_m$ arises from neural activation of the muscle. There are three processes associated with the activation block $H_a$ of Figure 1. Activation begins with a signal $u$ sent to alpha motor neurons in the spine that in turn activate the muscle fibres. The dynamics associated with the motor neurons are represented by a first order lag with time constant of 30 ms. There is also a lag associated with the activation and deactivation of the muscle fibres, set to 20 ms. Finally, the muscle fibres have some series compliance, principally due to the tendons. The effect of this compliance is modelled as another first order lag with time constant 50 ms. The series combination of the three first order lags define the $H_a$ block in Figure 1. The block has unity gain and zero phase at zero frequency.

The alpha motor neurons receive signals from two main sources. Signals can be sent directly from the motor cortex in the brain, in Figure 1 this signal is labelled $\alpha$. In addition the alpha motor neurons can be signalled by reflex action, which is predominantly a closed-loop feedback control of muscle length known as the stretch reflex. Gamma motor neurons in the spine activate special fibres in the muscle called spindles. The gamma motor neurons are believed to adjust the length of the spindles according to the muscle length (or handwheel angle) expected by the brain. If the muscle length differs from the expected length the spindles are strained and send a signal to the alpha motor neurons, which in turn activate the muscle to achieve the expected muscle length. The function of the muscle spindles is represented in Figure 1 by the summation circle, which
calculates the difference between the expected angle $\gamma$ and the actual angle $\theta$. The difference is then operated upon by a reflex gain $H_r$ and a delay $D_r$ before activating the muscle via the alpha motor neuron. In the present investigation the reflex gain is set to 0 Nm/rad or 50 Nm/rad, guided by the measurements in [8]. The reflex delay is largely a function of neural conduction velocities and the distance of the muscle from the motor neurons in the spine; the delay is set to 40 ms for tensed and relaxed conditions [6].

The stretch reflex system is a subject of ongoing research in the neuroscience field, for example [9], and there is at present incomplete understanding about its role in human motor control. The stretch reflex model presented in this paper is likely to be highly simplified but can be regarded as representative of first-order effects. In practice stretch reflex is known to have short-latency and long-latency components, the latter thought to be actively programmable by the brain. The reflex action is also thought to be sensitive to muscle velocity and force, as well as to muscle displacement.

3. OPEN-LOOP RESPONSE

The behaviour of the vehicle-steering-muscle-reflex system ($H_v, H_s, H_a, H_b, H_r$ and $D_r$) is investigated. The vehicle travels at constant speed $U=30$ m/s. Lateral tyre forces generated at the front axle are fed back to the pinion/handwheel via the torque $T_v$. The trail distance is $d=75$ mm. There is no closed-loop path following at this stage and thus there is no central activation of the muscle ($\alpha=0$ and $\gamma=0$). Using this model the effect of steering torque feedback arising from lateral force disturbances on the vehicle is calculated.

Figure 3(a) shows the vehicle lateral displacement response $y$ to a lateral force impulse of 500 Ns at the centre of mass $F_y$, for tensed muscles with 50 kN/m reflex gain (solid), tensed without reflex (dashed) and relaxed without reflex (dotted). In all three cases the pinion angle response is such that it causes the vehicle to gain steady velocity in the direction of the impulse disturbance. The global lateral velocity $\gamma$ is least for the tensed with reflex condition. This is because the reflex loop stiffens the steering's response to lateral tyre forces and thus reduces the amplitude of the pinion angle response. There is little difference in the response with tensed and relaxed muscles without reflex.

Note that for the case of no torque feedback ($d=0$ m, not shown) the muscle and steering system is not excited and thus independent of the muscle and reflex condition. In this case the final steady global lateral velocity $\gamma$ of the vehicle is zero (the final steady lateral displacement $y$ is 50 mm) thus the torque feedback in combination with the steering and muscle response can be regarded as having a deleterious effect on the response of the vehicle to lateral disturbances at the centre of mass.

The simulations were repeated for 500 Ns impulsive disturbances at the front and rear axle positions ($F_f$ and $F_r$). Figure 4 shows the resulting steady state global lateral velocity responses ($\gamma$). In the first group of three bars (1 on the horizontal axis) the results for the vehicle with locked steering are shown. If the steering is now free to steer, but the driver does not hold the steering wheel, the velocities shown in the second group of three bars (2) are obtained; the action of the lateral front tyre force acting on the steering mechanism results in a non-zero velocity response to $F_y$ compared to the locked steering case. If the driver now holds onto the steering wheel, either tensed or relaxed, but with no reflex action, the third and fourth groups of bars (3 and 4) are derived; it can be seen that the velocities are very similar to the hands-free case (2). This is because the response is determined mainly by the passive properties of the steering, which dominate over properties of the tensed or relaxed muscles.

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The effect of the path feedback is shown in Figure 3. The response to impulses applied at the front and rear of the car increases significantly compared to the no reflex cases (2 to 4), but the response to impulse at the centre of the vehicle decreases, as observed in the solid line of Figure 3(a). This is because the reflex action stiffens the arms and reduces the pinion angle response compared to the no reflex cases (2 to 4). The vehicle response thus tends towards that of the locked steering case (1) where the pinion angle response was zero. Thus the addition of reflex action can be seen to either increase or decrease the magnitude of the steady state global lateral velocity of the vehicle, depending on where the disturbance is applied to the vehicle.

4. CLOSED-LOOP PATH-FOLLOWING RESPONSE

In this section the generation of activation signals \( \alpha \) and \( \gamma \) by the brain to achieve path-following control is considered. The relevant blocks in Figure 1 are \( K, D_c, D_f \) and \( H_f \). Block \( D_c \) is a cognitive time delay that represents the information processing delay of the brain and the time for signals to travel from the sensory organs and to the motor neurons. In practice the various sensory channels differ in their time delay and frequency response; in the present work it is assumed that the system states are measured perfectly and that a single value of time delay applies. The time delay is implemented as a discrete-time shift-register [10] and is set to \( t_c = 0.5 \text{ s} \).

Block \( H_f \) is a forward-model of the delay-muscle-steering-vehicle system \( (D_c, H_a, H_b, H_s, H_r) \). The forward-model allows the pinion angle \( \theta \) response to a (pre-delay) activation signal \( \alpha_K \) to be calculated. The expected angle is the \( \gamma \) signal sent to the reflex system \( (H_f, D_r) \). If the forward model \( H_f \) is correct, and if there are no unexpected disturbances on the muscle-steering-vehicle system, then the expected angle \( \gamma \) exactly matches the true angle \( \theta \) and no reflex action occurs. The use of a forward model is an improvement over earlier driver-vehicle models [2,4,5] that used an inverse model with associated complications to ensure a proper transfer function.

The pre-delay activation signal \( \alpha_K \) is generated by control gains in block \( K \) acting upon the previewed lateral displacements \( y_l \) of the road path and upon the states \( x \) of the system \( (D_c, H_f, H_r, H_d, H_b, H_s, H_o) \). Preview of the road path is modelled by a discrete-time shift-register acting upon the road path lateral displacement \( y_p \) at a horizon \( t_o = 3 \text{ s} \) ahead of the vehicle. The control gains \( K \) can obtained using a discrete-time linear quadratic regulator (DLQR) or model predictive controller (MPC) [10,11,12]. The formulation involves a cost function \( J \) to be minimised, comprising the weighted sum of mean square values of lateral path following error, time integral of the lateral path following error and the \( \alpha_K \) activation signal. Note that the cost function does not account for the muscle activation required to maintain the tensed condition.

Time histories of lateral displacement \( y \) when a 500 Ns impulse is applied at the centre of the vehicle are shown in Figure 5(a). There are six lines on the graph. The three lines with larger displacement (black) correspond to tensed (solid), relaxed (dashed), and tensed plus reflex (dash-dot) conditions all with steering feedback. The effect of the path-following control is evident in the displacement eventually returning to zero, in contrast to the responses without path-following control shown in Figure 3(a). The smaller amplitude lines in Figure 5(a) (grey, laying on top of each other) are for no steering feedback. The corresponding pinion wheel angle responses are shown in Figure 5(b).

![Figure 4. Steady state global lateral velocities after lateral force impulse on the muscle, steering, reflex and vehicle model. Left hand bar \( F_r \), middle bar \( F_d \), right-hand bar \( F_f \). 1 = locked steering, 2 = hands-free steering, 3 = tensed without reflex, 4 = relaxed without reflex, 5 = tensed with reflex.](image-url)
The effect of the cognitive delay is now apparent. There is no preview of the force disturbance and thus the path-following control takes no action until the delay time \( t_d \) has passed. This is evident in Figure 5(b) for the three lines without feedback (grey); there is no driver response until the cognitive delay has passed. The graph shows zero pinion angle \( \theta \) until \( t > 0.5 \) s. With steering torque feedback the driver response from \( t=0 \) s to \( t=0.5 \) s arises from the passive and reflex behaviour of the neuromuscular system.

![Figure 5: Lateral displacement and pinion angle response to impulsive disturbance in \( F_d \) at \( t=0 \) s for tensed (solid), relaxed (dash) and tensed + reflex (dash-dot) conditions. The three larger amplitude responses (black) are with steering feedback, the three lower amplitude responses (grey) are without. Path-following controller enabled.](image)

The maximum lateral displacements of \( y \) are shown in Figure 6. There are six groups of three bars. Within each group the three bars correspond to impulses applied at the rear \( (F_r) \), middle \( (F_m) \) and front \( (F_f) \) of the vehicle. The first three groups of bars correspond to relaxed (1), tensed (2) and tensed plus reflex (3) conditions for the system with steering feedback. The second three groups (4 to 6) correspond to the same muscle conditions but without steering feedback. In all cases the final value of the path displacement is zero as a result of integral action in the path-following controller.

![Figure 6: Maximum lateral displacements after lateral force impulse. Left hand bar \( F_r \), middle bar \( F_m \), right-hand bar \( F_f \), 1-3 with feedback, 4-6 without feedback. 1, 4 = relaxed without reflex, 2, 5 = tensed without reflex, 3, 6 = tensed with reflex. Path-following controller enabled.](image)

When there is no steering feedback the relaxed (4), tensed (5) and tensed plus reflex (6) conditions all give similar maximum displacements to each other. The displacement magnitudes are smallest when the force disturbance is applied to centre of the car, and approximately equal to the displacement of 50 mm achieved by the vehicle with locked steering. In the first 0.5 s (before the path-following controller begins to act) the vehicle with no steering feedback responds as if there were no driver present. The displacement magnitudes achieved when the impulse is applied to the front or rear of the vehicle are about 0.4 m to 0.5 m and are strongly dependent on the cognitive delay. If the delay is increased, the vehicle displaces further away from the target path before the path-following controller takes action to return the vehicle to the target path.
The results for the systems with steering feedback are a little more complicated. Considering the impulse applied to the centre of the vehicle (middle bars of 1 to 3) the displacement is larger than the no feedback case (middle bars of 4 to 6). This is consistent with the steering feedback causing a pinion response that steers the vehicle away from the target path. The vehicle is then returned to the straight path by the path-following controller. The reflex acts to reduce the pinion response to steering feedback and thus the lateral vehicle displacement (middle bar, 3) is less than without reflex action (middle bars of 1 and 2). These results are consistent with the steady-state lateral velocities arising when the path-following controller is absent, Figure 4. The displacement magnitudes arising from impulses at the front ($F_f$, left hand bar of 1 to 3) and rear ($F_r$, right hand bar of 1 to 3) of the vehicle can similarly be understood by referring to Figure 4.

5. CONCLUSION
A driver-vehicle model was assembled with steering torque feedback and neuromuscular dynamics, including stretch reflex, but initially without path-following control. Lateral impulsive disturbances on the vehicle with steering torque feedback resulted in excitation of the neuromuscular and steering system, leading to modification of the vehicle's directional response to the disturbance. Tensing or relaxing the muscles (modifying the intrinsic properties) made little difference to the directional response, but the stiffening effect of the reflex action had a significant effect, dependent on the longitudinal position of the disturbance.

A path-following controller was implemented, including a cognitive time delay and a forward model for generation of the reflex demand (gamma) signal. The lateral displacement response of the vehicle to lateral force impulse on the vehicle was strongly dependent on: longitudinal position of the impulse; amount of steering torque feedback; cognitive time delay; and reflex gain.

The results highlight the significance of the NMS and steering dynamics in determining the vehicle response to disturbances. The model is thought to provide a suitable basis for investigating the interaction between a driver and semi-autonomous steering controls (for example, steering torque and angle overlay). However, further understanding of the behaviour of the NMS is desirable: how does the driver decide to co-contract muscles; how does reflex action depend on the contraction state of the muscles; and how are reflex actions consciously or subconsciously modified?

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References
[1] www.vehicle dynamics.org