

Development of the Next-Generation Steering System (Development of the Twin Lever Steering for Production Vehicle)

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ABSTRACT

Looking back on steering systems in more than a hundred years that have passed since the introduction of the automobile, it can be seen that original method of controlling cars pulled by animals such as horses was by reins, and early automobiles had a single push-pull bar (tiller steering). That became the steering wheel, and an indirect steering mechanism by rotating up and down caught on.

While the steering wheel is the main type of steering system in use today, the team have developed the Twin Lever Steering (TLS) system controlled mainly by bi-articular muscles, making use of advancements in science and technology and bioengineering to develop based on bioengineering considerations as shown in Fig. 1. The objective of that is to establish the ultimate steering operation system for drivers.

In the first report, the authors reported on results found by using race-car prototypes as shown in Fig. 2. Advantages in terms of bioengineering are (1) force can be exerted more easily, (2) steering can be accomplished quickly, (3) positioning can be done accurately, and (4) burden on the driver can be reduced (less fatigue). Advantages in terms of vehicle motion are (1) line-traceability is improved and (2) lap time is improved and steering layout is safe.

Herein, creating a TLS system using prototype vehicles based on those on the market and verification test results will further be reported.

INTRODUCTION

In recent years, the possibility of constructing a new steering system is now quickly gaining popularity through the introduction of new technologies such as by-wire operation and active control. In light of that situation, it will become important to create a steering system thought up centered on the “Human” to create a vehicle which, regardless of the driving experience or the age of the driver, can be controlled easily and proficiently just as the driver desires. In steering operations in particular, driver upper limb control abilities of strength, speed, and positioning are required for driving situations that change by the moment. It is also especially important to optimize the motions of the driver's upper limbs.

From a regulatory standpoint, the steering system that makes that possible must have tire and steering control parts mechanically linked. It is thus important that the steering system mechanism to be optimized.

In the first report results and observations were discussed regarding equipping TLS to racing vehicles (F1 cars, Formula Honda) and conducting circuit tests by drivers with top-class driving skills. For vehicle dynamics, reduced operation time and turn time, stabilized steering characteristics, and improved lap time were achieved. For driver dynamics, stabilized head behavior, stabilized driver's body pressure on the seat, and reduction in total tire steering angle change per lap were realized.

In this paper, the results of verifying effects by general drivers and the effects gained in both vehicle dynamics and driver dynamics with prototype vehicles based on production vehicles will be reported.

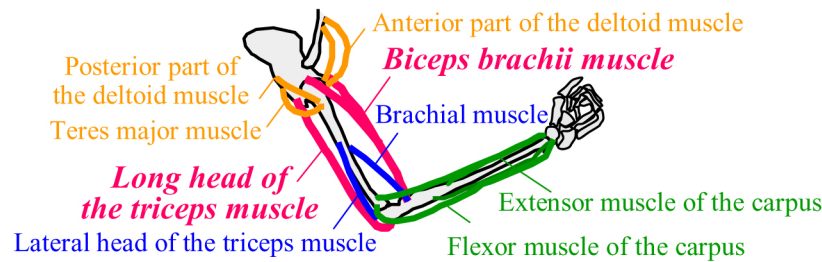


Figure 3. Upper limb muscles

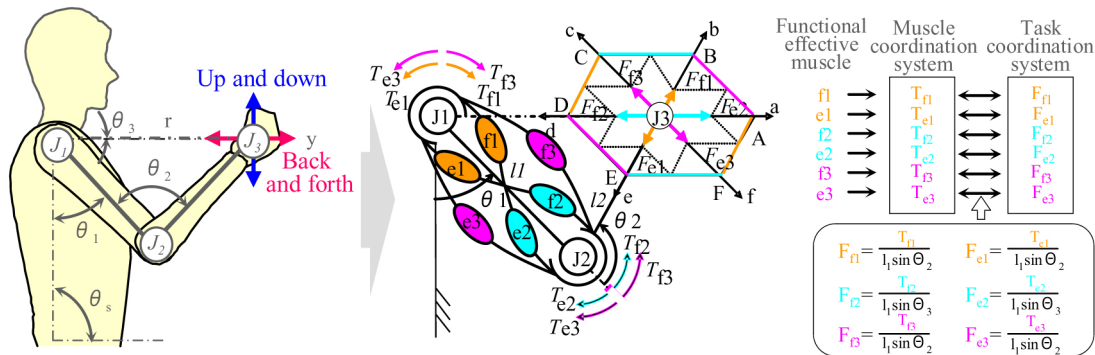


Figure 4. Theory of coordinated control exerted by muscles

DRIVER AND VEHICLE CONTROL THEORY

In recent years, it has gradually become clear that the bi-articular muscles are crucial to motion control of the distal extremities as shown in Fig. 3. The theory of control achieved in a coordinated manner between mono-articular and bi-articular muscles has been formed by Prof. Kumamoto, et al. [3],[4]

THEORY OF COORDINATED CONTROL EXERTED BY MUSCLES

The theory of coordinated control exerted by muscles is a theory that models the motions of the upper limbs and clarifies the relationship between the force generated by each muscle and the distribution of the output force exerted by the wrist joint. That theory, as shown in Fig. 4, makes possible the distribution of the output force delivered by the wrist joint being approximated to a hexagon. It shows that operation in the back-and-forth direction implies a closer relationship between output muscles and the direction of motion, as compared with operation in the up-and-down direction, and that it is possible to improve motion controllability.

In this study, as shown in Fig. 4, the steering operation was roughly divided into two components: operation in the normal (back-and-forth) direction and that in the tangential (up-and-down) direction. This division was made in terms of a circle centered on the shoulder joint and with the radius (r)

equal to the distance between the shoulder joint and the wrist joint. Then, the project compared the data to verify the operability[5],[6].

DRIVER CHARACTERISTICS[2],[6]

Figure 5 (a) illustrates the maximum output force of the wrist joint motion when the elbow joint angle is 135° as the typical driving positions of the driver. When the elbow joint angle is approx. 60° or larger, greater force can be exerted more easily in the back-and-forth direction than in the up-and-down direction.

For characteristics of the output velocity[7], the team asked the subject to move the wrist joint back and forth as quickly as possible starting from the basic posture, and measured the velocity. The basic arm posture was considered to be that where the elbow joint angle is 90° (i.e., when manipulability reaches its maximum), and the wrist joint velocity was measured at five measurement points within the interval of ±100 mm from the basic arm posture in the back-and-forth as well as the up-and-down direction. Motion velocities in the back-and-forth direction are greater than those in the up-and-down direction as shown in Fig. 5 (b).

Tracking test results obtained by means of a simulator are shown in Fig. 5 (c). The right-hand portion of Fig. 5 (c) shows a comparison of the deviations between a steering wheel and TLS obtained in two different cycles. The deviations in operation in the back-and-forth direction are

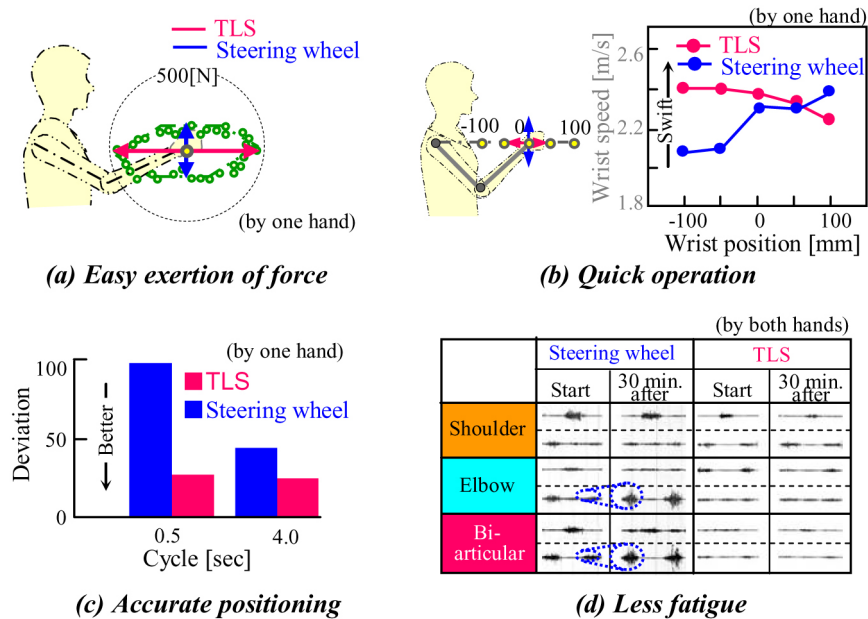


Figure 5. Advantages of TLS (driver Dynamics)

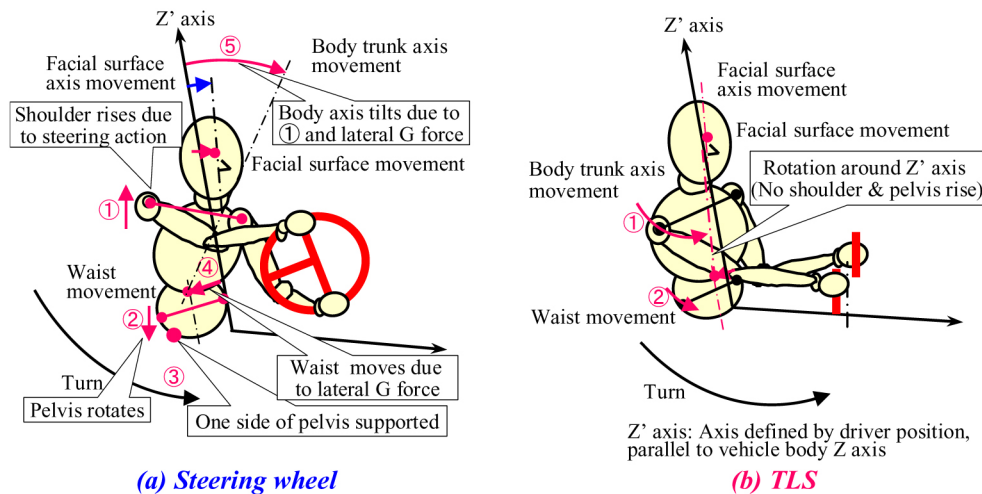


Figure 6. Mechanism of driver behavior during steering operation

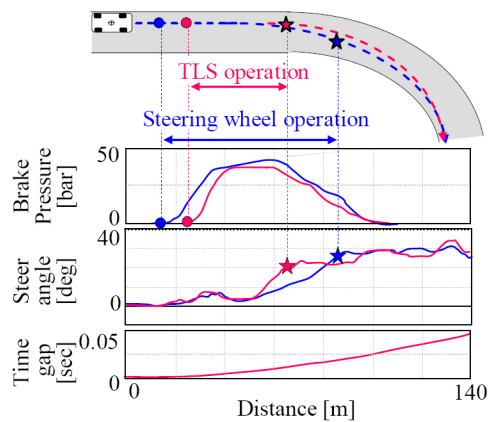
smaller than those in the up-and-down direction. That means better tracking of the target position can be obtained, and there is little deterioration in performance as time passes.

Figure 5 (d) shows a comparison between the changes in the myoelectric potential obtained at various positions of the operator (shoulder muscles, elbow muscles and bi-articular muscles) with a steering wheel and TLS. Smaller changes were observed in the electromyography, indicating less fatigue with TLS than with a steering wheel. In other words, the operator will feel less fatigue when operating TLS than when operating a steering wheel.

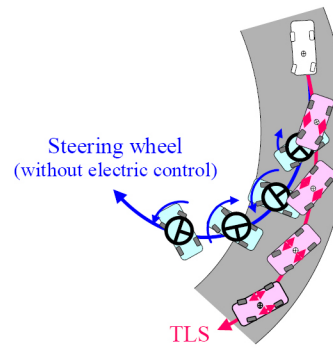
DRIVER BEHAVIOR^[2]

Figure 6 shows the mechanism of driver behavior during steering operation. The shoulder rises when operating a steering wheel operation due to the steering action, then the pelvis rotates and one side of the pelvis is supported. G forces are applied at that time, there is a tendency for the waist to move sideways due to those G forces, the trunk axis tilt, and finally the head tilt and sight line move.

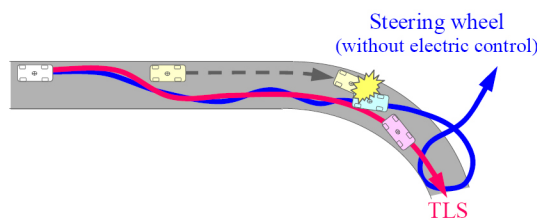
With TLS operation, however, a rotation operation is made around driver's trunk axis. Thus, shoulder and pelvis do not move upward and downward, and the trunk axis, head, and sight line are more stable.



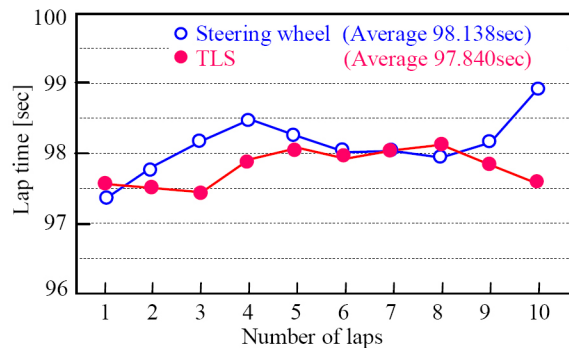
(a) Line traceability



(b) Drift control performance



(c) Lane-changeability



(d) Lap times and better stability

Figure 7. Advantages of TLS (Vehicle Dynamics)

VEHICLE CHARACTERISTICS^[2]

The TLS advantages of the vehicle in terms of its motion are as follows: (a) the line-traceability is improved, (b) the drift control is improved, (c) the lane-change capability is improved, and (d) the lap time and stability are improved as shown in Fig. 7.

As compared with the steering-wheel vehicle, the TLS-equipped vehicle allows a decrease in the total steering angle and lap time, as well as making the vehicle more stable. Thus, it can also decrease the amount of overshoot and the convergence time, both of which are involved in lane change performance.

Block diagram

Figure 8 shows a block diagram and driver model during steering operation.

The driver model is generally composed of dead time, first-order lag constant, first-order lead constant, and gain in relation to target deviation as control factors. The first-order lag constant and gain depend on driving ability in driver prediction/judgment and operations to adapt.

Dead time, on the other hand, is nervous system and judgment lag. First-order lag constant is the time up to receiving the command from the nerves to the muscles stiffening and turning the steering wheel completely to the steering angle. First-order lag constant is considered to depend on the operation method.

Taking improvement of emergency avoidance performance as an example, the avoidance operation requires quick steering speed to avoid obstacles faster. The recovery operation requires accurate positioning and good convergence in steering operation to more quickly restore the vehicle to the intended course and make behavior stable.

Prediction of effects by steering stability simulation

Optimizing steering control performance for driver and vehicle systems in total was studied.

To achieve optimized steering control, this time the project verified by simulation whether or not emergency avoidance performance could be improved. Methods of improving were steering differential control according to steering speed in avoidance steering and steering characteristics minimization (vehicle body slip angle control) control in restoration steering.

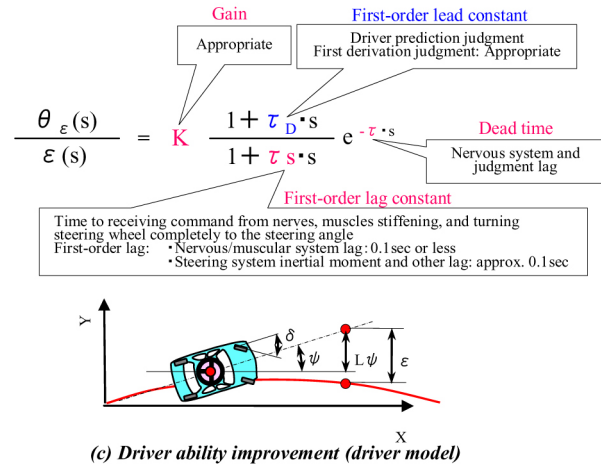
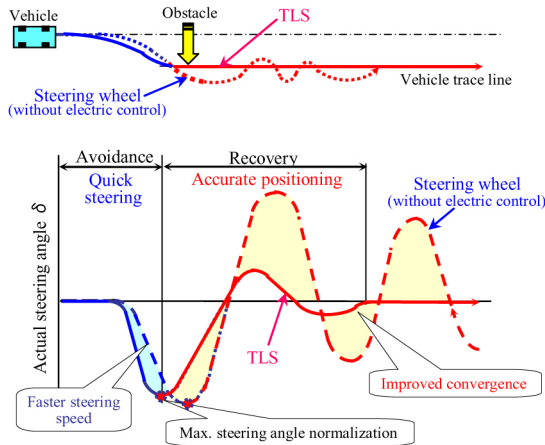
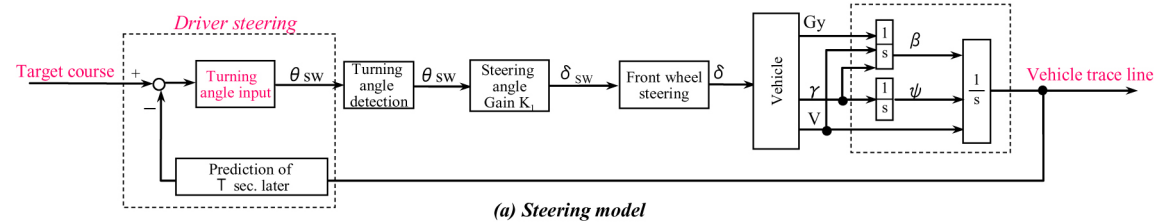


Figure 8. Vehicle body behavior

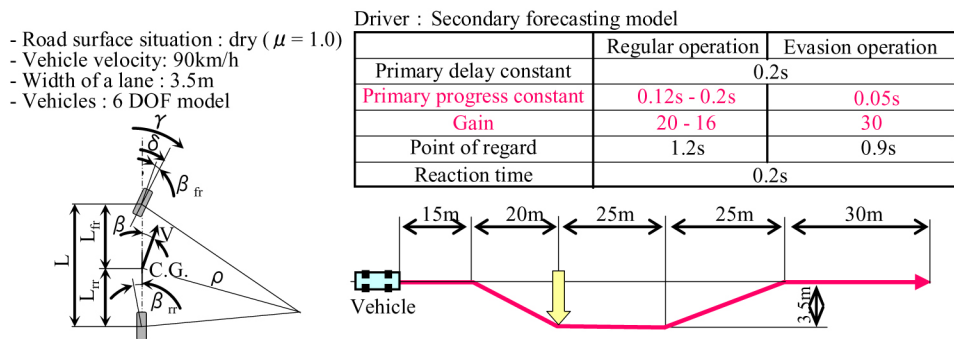


Figure 9. Simulation model

Simulation was conducted with...

Total steering angle = Steering angle of conventional steering wheel input
+ Differential steering angle (at avoidance operation)
+ US/OS control steering angle (at restoration operation)

(1)

$$\ddot{a} = \ddot{a}STW + \ddot{a}V + \ddot{a}OS/US$$

(2)

As Fig. 9 shows, a six-degree of freedom model was used for the vehicle model and a secondary prediction model used for the driver model in the simulation to study skilled and unskilled drivers. As a result, the simulation results for unskilled drivers are shown in Fig. 10.

From the simulation results shown in Fig. 10 also, performance improvement could be predicted from steering speed in avoidance operation and accurate positioning in recovery operation.

PROTOTYPE VEHICLES

Prototype vehicles were designed and built based on production vehicles equipped with the TLS system in which back-and-forth operations were carried out along a straight line connecting the shoulder and the wrist. The steering mechanism of these prototype vehicles has the steering wheel and the operation grip linked mechanically just as the race-car in the first report.