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Performance of Four-Wheel-Steering Vehicles in Lane Change Maneuvers

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Abstract

This study addresses the performance of four-wheel-steering vehicles in high-speed lane change maneuvers. We first compare the recorded steering command of an experienced driver in executing a lane change maneuver with that determined via solving a suitably formulated optimization problem, and found them to be qualitatively comparable. This finding allows us to analytically compare the optimal lane change performance achievable with both two and four wheel steering vehicles. For a representative high-speed lane change maneuver, our study revealed that, in the hands of an experienced driver, the performance benefit achievable with four-wheel-steering vehicles is not significant. This conclusion is in agreement with road-test results obtained with two production four-wheel-steering vehicles. The applicability of the proposed "optimal control" approach in evaluating the performance of other driver-vehicle maneuvers is an interesting topic for future study.

Introduction

Four-wheel-steering (4WS) systems for passenger vehicles have been actively studied recently [1]. The performance of these systems depends largely on how the rear wheels are controlled as functions of vehicle speed, steering angle, and others. These rear steering controllers are usually designed to improve: (a) vehicle maneuverability at low speed, and (b) straight-line stability at high speed. The performance of four-wheel-steering vehicles in high-speed lane change maneuvers has not been adequately addressed.

This study addresses the relative performance of 2WS and 4WS vehicles in high-speed lane change maneuvers. First, we study the recorded steering command of an experienced driver in executing a high-speed lane change maneuver. It turns out that the road test result is qualitatively comparable with that determined via solving a suitably formulated optimization problem. This finding then allows us to analytically compare the optimal lane change performance achievable with both 2WS and 4WS vehicles.

Vehicle Dynamics Model

Consider a vehicle moving over a flat and level road surface (Fig. 1). When the forward speed, U, is kept constant, this vehicle model has two degrees-of-freedom, the side velocity, V, and the yaw-rate, r. The cornering forces acting on the front and rear axles are denoted by F_f and F_r, respectively. Apart from these forces, there are the relatively small aligning torques, camber angle effects, etc. that are neglected in our study.

In Fig. 1, a and b define the location of the vehicle's c.g. between the axles, and M_s and I_{zz} denote the mass and the yaw moment of inertia of the vehicle, respectively. Furthermore, if C_{af} and C_{ar} denote the cornering stiffnesses of each front and rear tire, respectively, and if δ_f and δ_r denote the front and rear steer angles, respectively, then the vehicle's equations of motion are [3]:

$$\begin{aligned} I_{zz}\dot{r} &+ \frac{2(a^2C_{\alpha_f}+b^2C_{\alpha_r})}{U}r \\ &+ 2(aC_{\alpha_f}-bC_{\alpha_r})\frac{v}{U} \\ &= 2aC_{\alpha_f}\delta_f - 2bC_{\alpha_r}\delta_r\,, \qquad (1) \\ M_s\dot{v} &+ \{M_sU + \frac{2(aC_{\alpha_f}-bC_{\alpha_r})}{U}\}r \\ &+ 2(C_{\alpha_f}+C_{\alpha_r})\frac{v}{U} \\ &= 2C_{\alpha_f}\delta_f + 2C_{\alpha_r}\delta_r\,. \qquad (2) \end{aligned}$$

In our study, the vehicle model is augmented with the following first-order actuator dynamic models

$$\tau_f\dot{\delta}_f + \delta_f = \delta_{fc}\,, \qquad (3)$$
$$\tau_r\dot{\delta}_r + \delta_r = \delta_{rc}\,. \qquad (4)$$

Here δ_{fc} and δ_{rc} are commands to the front and rear actuators, respectively. In (3-4), τ_f and τ_r are the time constants of the front and rear actuators, respectively. In our study, we assumed that the bandwidth of these actuators is 4 Hz. Also, we assume the following vehicle parameters: $[a,b]$ = [1.2, 1.6] m, I_{zz} = 2200 kg-m^2, M_s = 1700 kg, $[C_{\alpha_f}, C_{\alpha_r}]$ = [960, 1100] N/deg. The validity of this vehicle model begins to deteriorate in maneuvers with lateral acceleration higher than 0.3 g's, including those found in high-speed lane change maneuvers. However, the situation is mitigated somewhat by the fact that these high-g conditions only lasted for a short time. What follows does not depend on the "linear" vehicle model assumption which was used only for convenience. Nonlinear vehicle models that can better predict vehicle responses in high-g maneuvers should be used if available.

In addition to these dynamic equations, the following kinematical relations are used to compute the resultant vehicle trajectory:

$$\dot{\psi} = r, \qquad (5)$$
$$\dot{x} = U\cos\psi - v\sin\psi, \qquad (6)$$
$$\dot{y} = U\sin\psi + v\cos\psi. \qquad (7)$$

In Fig. 1, (x,y) is the recti-linear coordinates of the vehicle's c.g. relative to an arbitrary reference. In Fig. 4, the angle ψ is that between the vehicle's longitudinal axis and the x-axis, and is defined positive in the clockwise direction.

Open and Closed-loop 4WS Algorithms

Using the vehicle model given above, we can design the following open-loop and closed-loop 4WS algorithms:

4WSN Algorithm This is an open-loop algorithm suggested by Nissan Motor Company. Using a vehicle model, a speed-dependent ratio between the rear and front wheels is computed in order to achieve zero steady-state side velocity: $\delta_{rc}/\delta_{fc} = K_N(U)$, where U is the forward speed of the vehicle. At high speeds, the rear wheels are steered in-phase with respect to the front wheels to enhance the vehicle lateral stability. However, the lateral forces generated by both the front and rear wheels counteract with one another, and the response time of the vehicle's yaw rate deteriorated. To overcome this problem, we delay the execution of the rear wheel command by τ_D [1]:

$$\delta_{rc}(t) = K_N(U)\,\delta_{fc}(t-\tau_D)\,. \qquad (8)$$

With τ_D = 0.08 seconds, the "delayed" Nissan algorithm produced good lateral response characteristics. Numerous other open-loop algorithms have also been suggested [2].

4WSY Algorithm This is a simple closed-loop algorithm with feed-through of the front steering command and feedback of the vehicle's yaw-rate

$$\delta_{rc} = -K_{rc}\,\{Y_G(U)\delta_{fc} - (\frac{1+\tau_1 s}{1+\tau_2 s})\,r\,\}\,. \qquad (9)$$

The function $Y_G(U)$ is a speed-dependent yaw velocity gain (steady state yaw rate per unit front tire angle excursion) of the 2WS vehicle. An "anticipatory" lead term $(1+\tau_1 s)$ is used to improve the vehicle response speed, and τ_2 is the time constant of a low-pass filter. For simplicity, we let K_{rc} = 2.5 seconds at all vehicle speeds. Other closed-loop algorithms have also been proposed in the literatures [3].

Lateral Characteristics of 2WS and 4WS Vehicles

The lateral acceleration gains of the 2WS, 4WSN, and 4WSY vehicles as functions of vehicle speed are compared in Fig. 2. These gains are defined as the steady-state values of the vehicles' lateral accelerations per unit front tire angle excursion. Note in Fig. 2 that the steady-state gains for the 2WS and 4WSY vehicles are identical because the 4WSY vehicle, like the 2WS vehicle, produces no rear steering angle in the steady state. On the other hand, the rear wheels of a 4WSN vehicle are steered in-phase with the front ones, leading to a drop in the lateral acceleration gain. This is undesirable because the driver must now execute a larger steering angle (relative to that needed for a 2WS vehicle) in order to generate the same level of lateral acceleration. A common remedy for this drawback is to increase the steering ratio of the 4WS vehicle, but this is not assumed in this studdy.

Transient yaw rate responses of the 2WS, 4WSN, and 4WSY vehicles are compared in Fig. 3. These transient responses are obtained with steering commands linearly ramped to their steady-state values (~ 0.5 deg) in 0.15 seconds. The percent overshoots (M_P) and 90% rise-times (T_T) of these vehicles' yaw rate and lateral acceleration responses at a forward speed of 120 km/h are tabulated in Table 1. Here, we observe that both the 4WSN and 4WSY vehicles' yaw rate responses are faster and better damped than that of the 2WS vehicle. The rise time of the 4WSN vehicle's lateral acceleration response is also significantly smaller than its 2WS vehicle's counterpart. With these faster and better damped lateral response characterisitcs, can one then expect an improved lane change performance with either the 4WSN or 4WSY vehicle?

Performance of Driver-Vehicle System in Lane Change Maneuvers

The performance of driver-vehicle in collision avoidance maneuvers is difficult to evaluate because one must take both the vehicle's directional characteristics as well as the limitations of driver responses into consideration. Several collision avoidance scenarios had been studied in the literatures [4-7]. In this study, we constructed a particularly simple scenario illustrated in Fig. 4. Here, a vehicle is travelling at a constant speed on a straight two-lane roadway when an object dashes into the vehicle's path and stops. Driver reactions when faced with such an emergency typically involved first a 0.3-0.4 seconds delay time [4]. Braking is next used to decelerate the vehicle, but this by itself may not be sufficient and the vehicle must be quickly and skillfully steered to a neighboring lane to avoid an accident.

Road tests of constant-speed lane change maneuvers had been conducted using both experienced and inexperienced drivers [4]. Representative time histories of steering wheel excursions recorded are given in Fig. 5. As depicted, the initial steering commands generated by both driver groups are similar. The maximum steering angles and steering rates for both driver groups are on the order of 200 degrees and 800 deg/sec, respectively. The initial steering command must be followed by an almost "equal-and-opposite" steering in order to arrest the diverging vehicle's heading angle, and return it back to the desired straight-ahead heading.

In this study, we conjecture that experienced driver steering commands in a lane change maneuver can be partitioned into a reflexive phase followed by a regulatory phase (Figs. 5 and 6). We further conjecture that a driver will, based on his "crude" estimates of vehicle speed and lane width, execute a series **of** well-learned steering commands during the reflexive phase, in "open-loop." In the regulatory phase, the driver will use small steering adjustments to "zero" out residuals in the vehicle's yaw rate, side velocity, and heading angle, in "closed-loop."

Optimal Vehicle Control in A Lane Change Maneuver

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From results given in Figs. 7 and 8, and those given in Table 2, our study indicated that the performance benefit achievable with four-wheel-steering vehicles in high-speed lane change maneuvers is not significant for experienced drivers. This conclusion contradicts results found in other research which concluded that driver/4WS vehicle performed better than driver/2WS vehicle in collision avoidance maneuvers [6]. However, we note that the driver model used in Ref. 6 was one developed for 2WS vehicles, and it might not be appropriate to use it in studies involving 4WS vehicles. Moreover, this "4WS vehicle can enhance lane change maneuvers" conclusion is not an unanimous one [9-l 1].

In comparing road-test results obtained with both the 2WS and 4WS versions of a production car model, the editors of Car & Driver commented: "... In two days of over-the-road experience with both the two-wheel-steering and four-wheel-steering vehicles, two Car & Driver editors simply could not detect any handling differences between them" [l0] Comments made by the editors of *Motor Trend* on another 4WS production vehicle model are similar: "... At speed, lane-change maneuvers don't feel different enough to get your attention" [ll]. Results obtained from the present analytical study are hence consistent with those found in road tests.

From Table 1, we note that 4WS vehicles have better lateral response characteristics than those of 2WS vehicles. However, our study indicated that these "improved" lateral response characteristics does not translate into better lane change performance for experienced drivers. This mediocre correlation between the lateral response characteristics and lane change performance had also been observed in Ref. 5. Therefore, in designing 4WS controllers, attention should be paid not only on improving the vehicle's lateral response characteristics but also on how the "combined" performance of the driver-vehicle can be enhanced by the 4WS controller.

Conclusions

The steering command used by an experienced driver during the reflexive phase of a high-speed lane change maneuver has been found to be comparable to that obtained via solving a suitably formulated optimal control problem. This finding allows us to analytically compare the optimal lane change performance achievable with both 2WS and 4WS vehicles. For a representative high-speed lane change maneuvers, our study revealed that, in the hands of an experienced driver, the performance benefit achievable with four-wheel-steering vehicles is not significant relative to that achieved using a two-wheel-steering vehicle. This conclusion is in agreement with road test results obtained on two production four-wheel-steering vehicles. However, our study is limited in scope, and this finding must be confirmed via future comprehensive investigations (using a nonlinear vehicle model that has been validated against "high-g" maneuvers). The applicability of the proposed "optimal control" approach in evaluating the performance of other driver-vehicle maneuvers is an interesting topic for future study.

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Table 1. Vehicle Transient Response Characteristics at 120 km/h

Criterion	2WS	4WSN	4WSY
M_p (%) $[r]$	20	6	2
T_r (sec) $[r]$	0.25	0.15	0.15
M_p (%) $[a_{yy}]$	3	4	0
T_r (sec) $[a_{yy}]$	0.48	0.23	0.45

Table 2 Relative Performance of Vehicles in Lane Change Maneuvers

Vehicle	J	T (sec)	ψ_T (o)	δ_{fT} (o)	$\bar{a}_{yy}$ (g's)	$\dot{\delta}_{fc}$ (°/s)
2WS	29.57	1.48	5.2	0.34	0.37	162
4WSN	29.33	1.48	4.9	0.06	0.37	171
4WSY	29.40	1.45	5.5	0.11	0.38	134

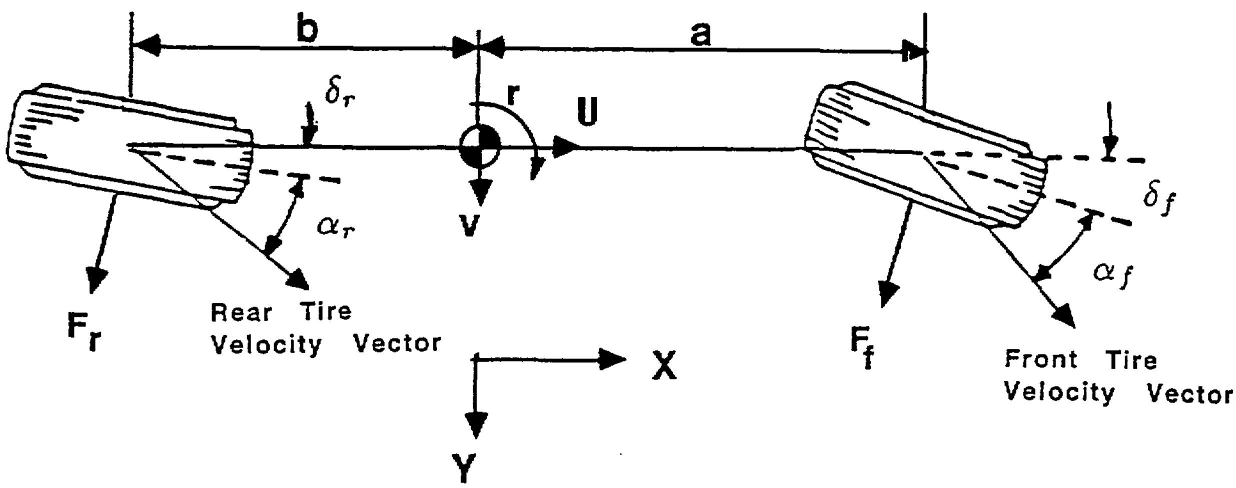

Fig. 1 Schematic of A Vehicle Handling Model

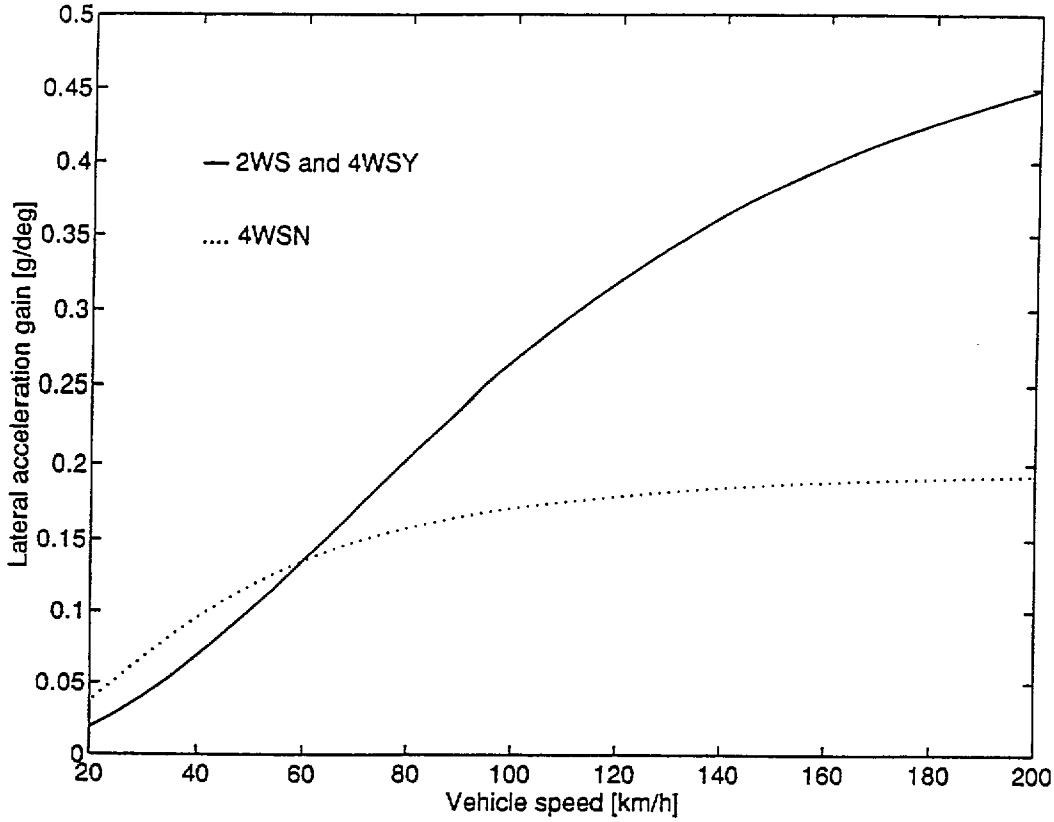

Fig. 2 Variations of Acceleration Gains with Vehicle Speed

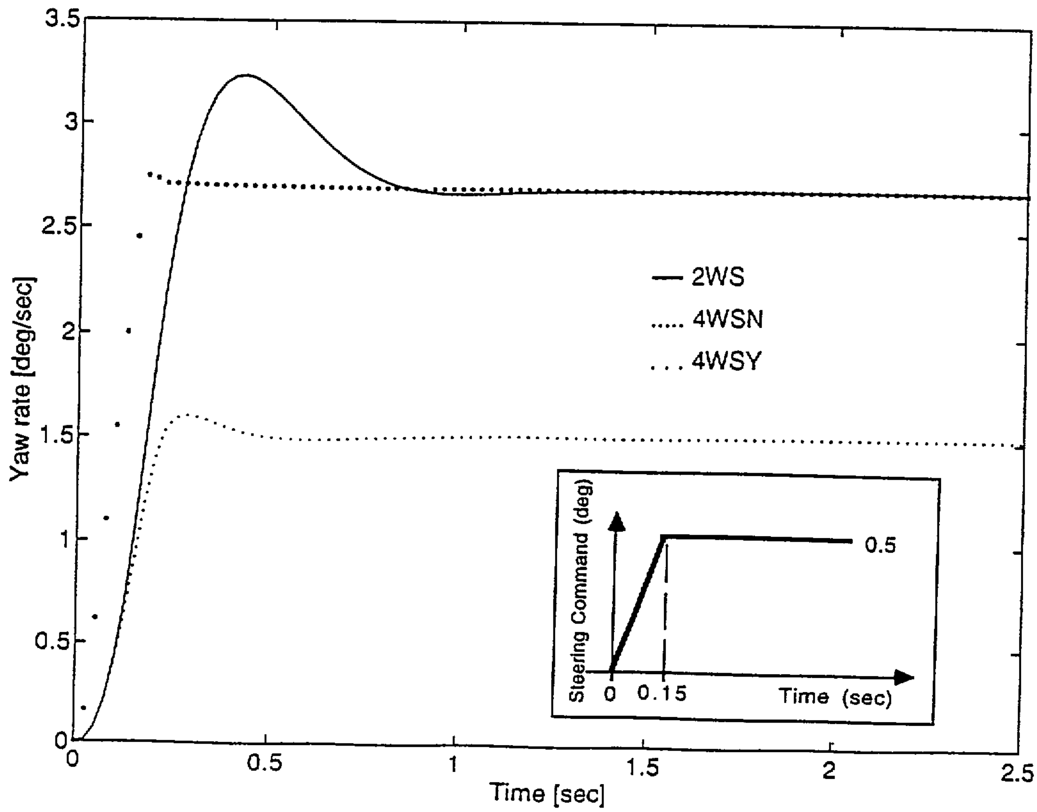

Fig. 3 Yaw Rate Time Responses at 120 km/h

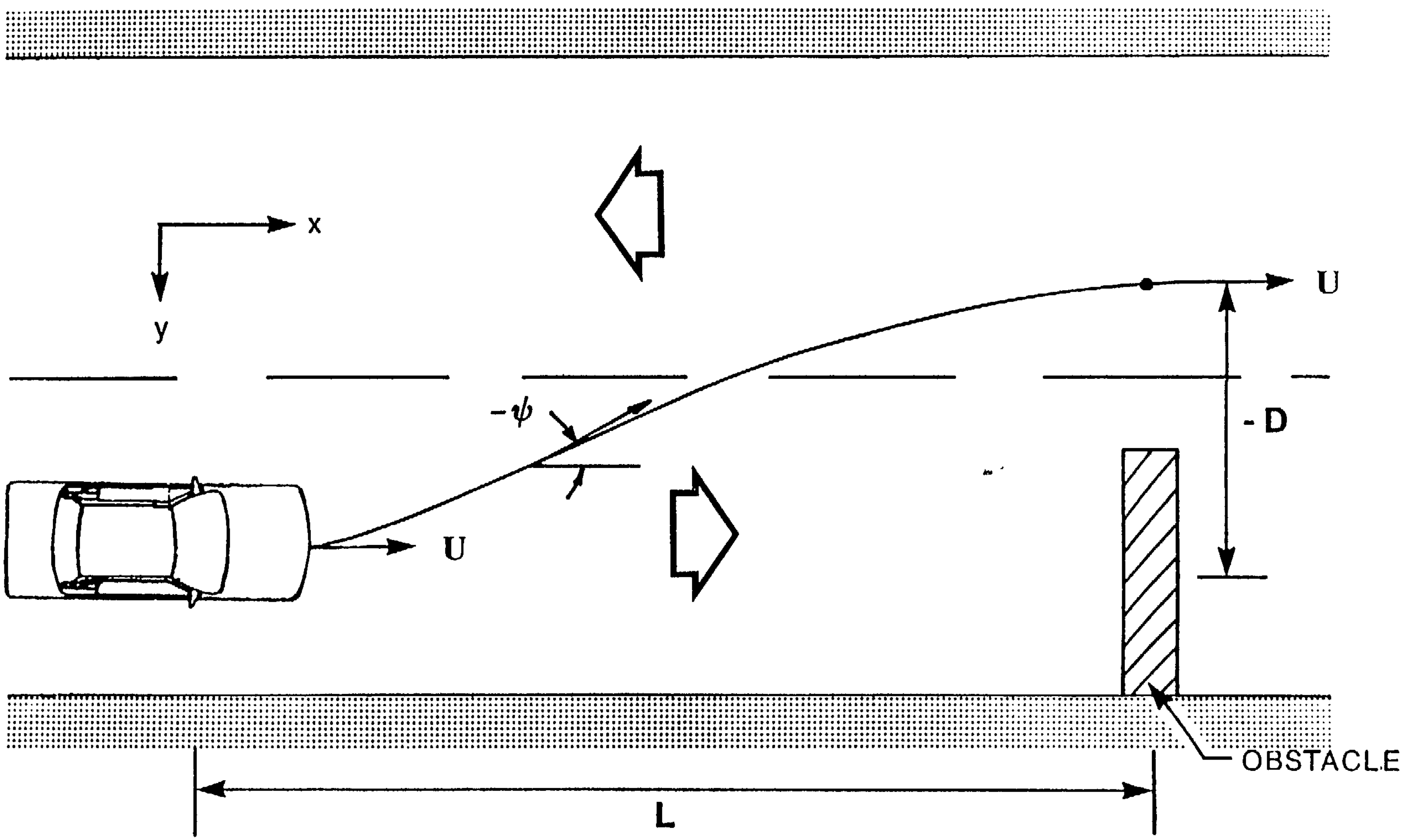

Fig. 4 Schematic of Lane Change Maneuver

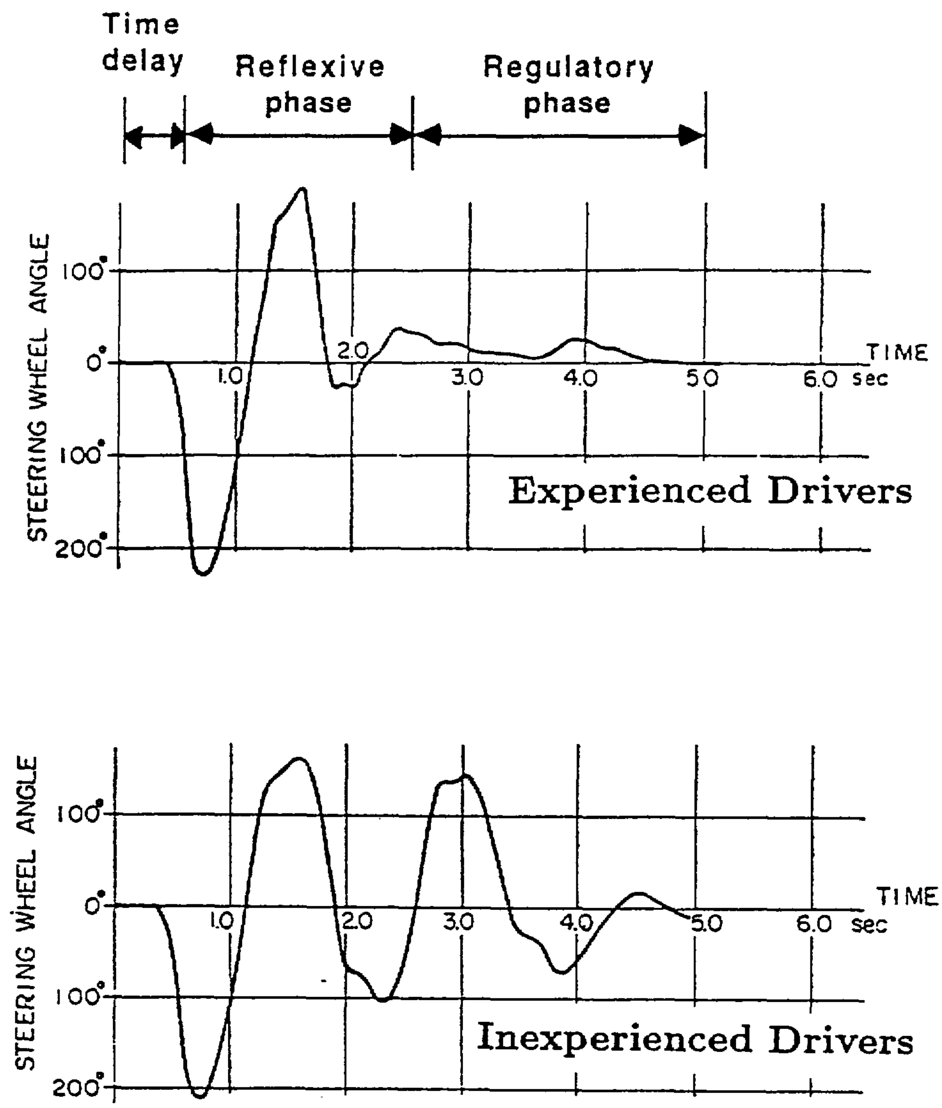

Fig. 5 Recorded Steering Time Histories in Lane Change [4]

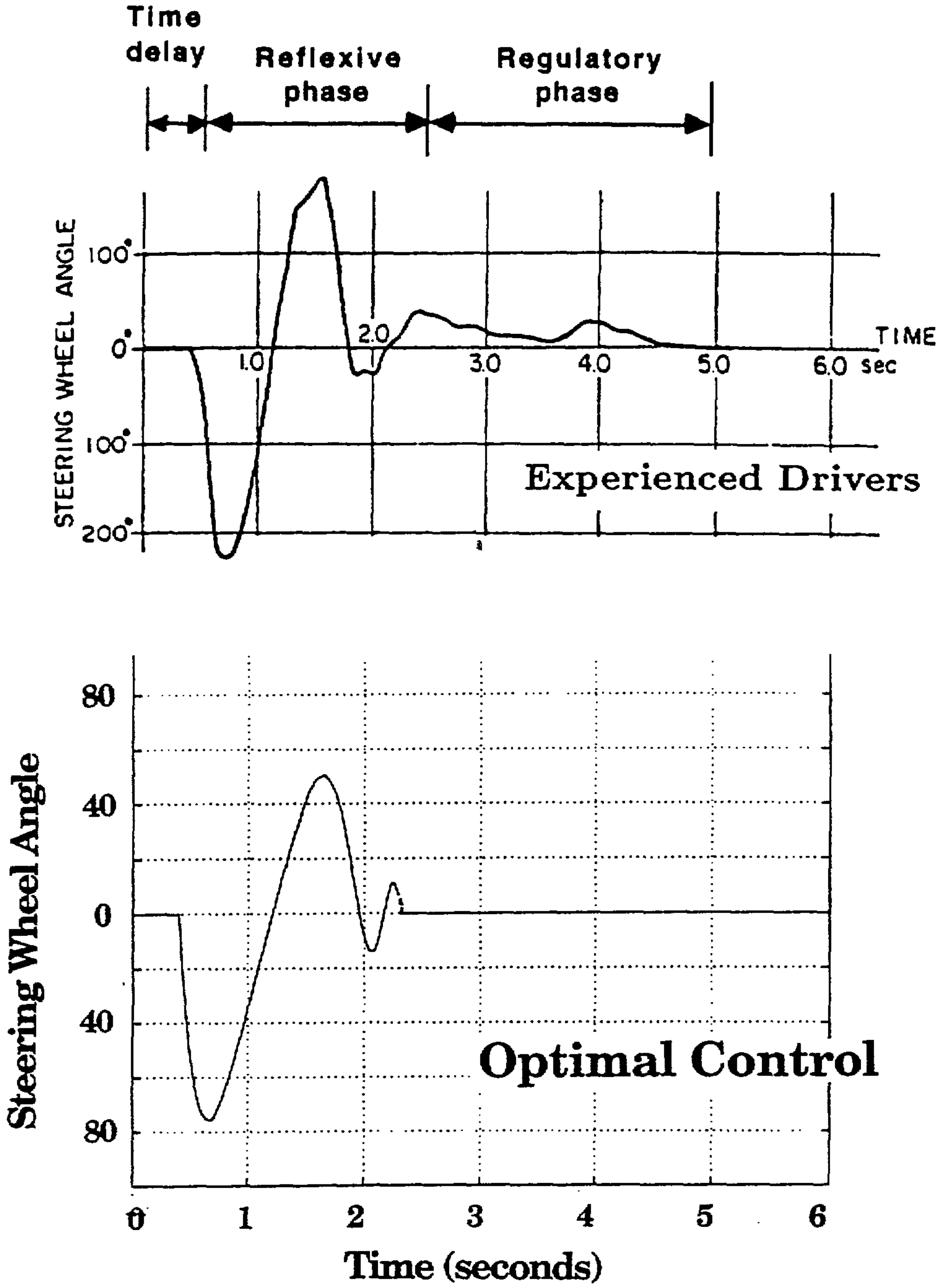

Fig. 6 A qualitative comparison between steering command used by experienced drivers and that obtained via solving an optimization problem

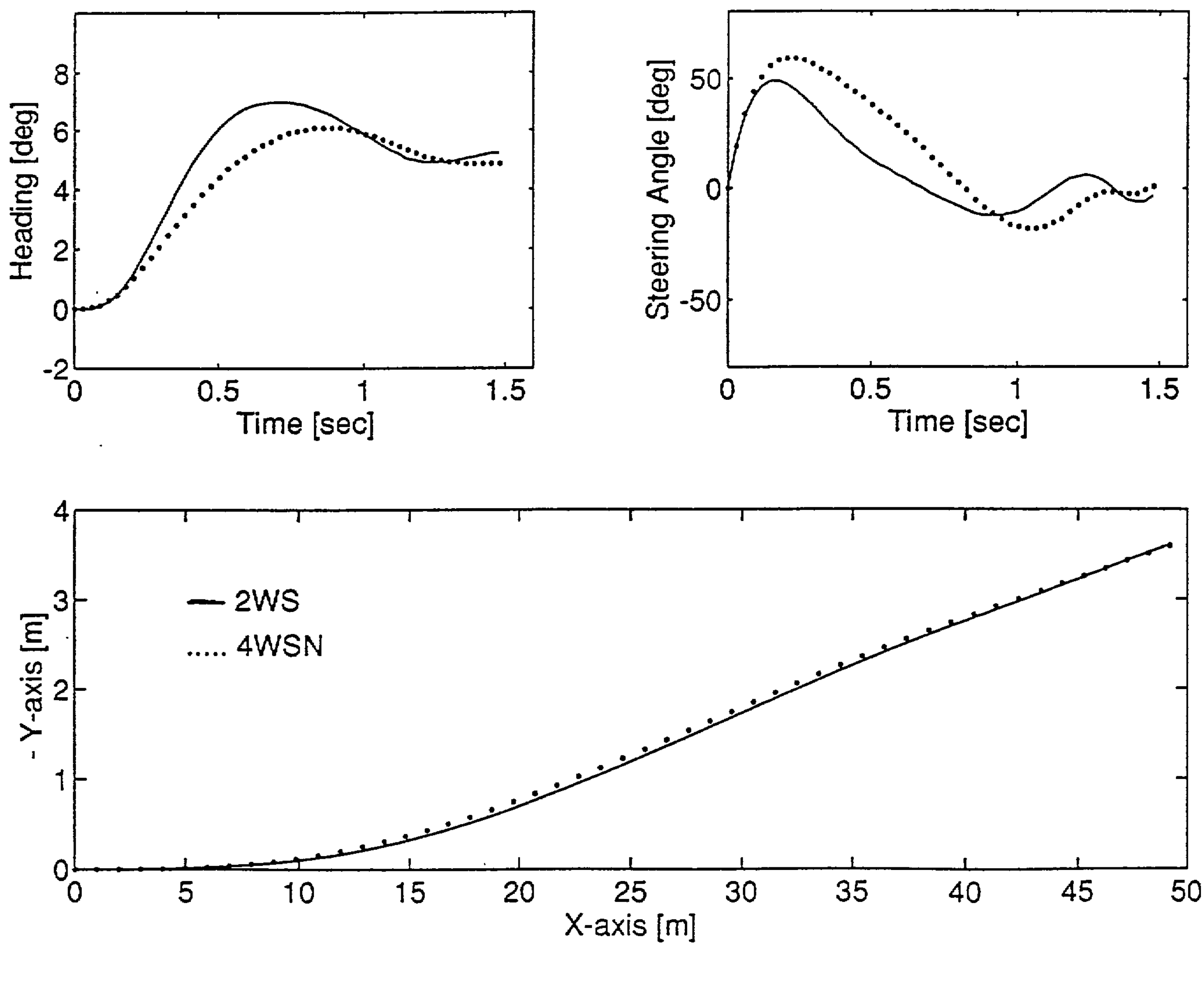

Fig. 7 Comparison of lane change maneuvers (2WS vs 4WSN)

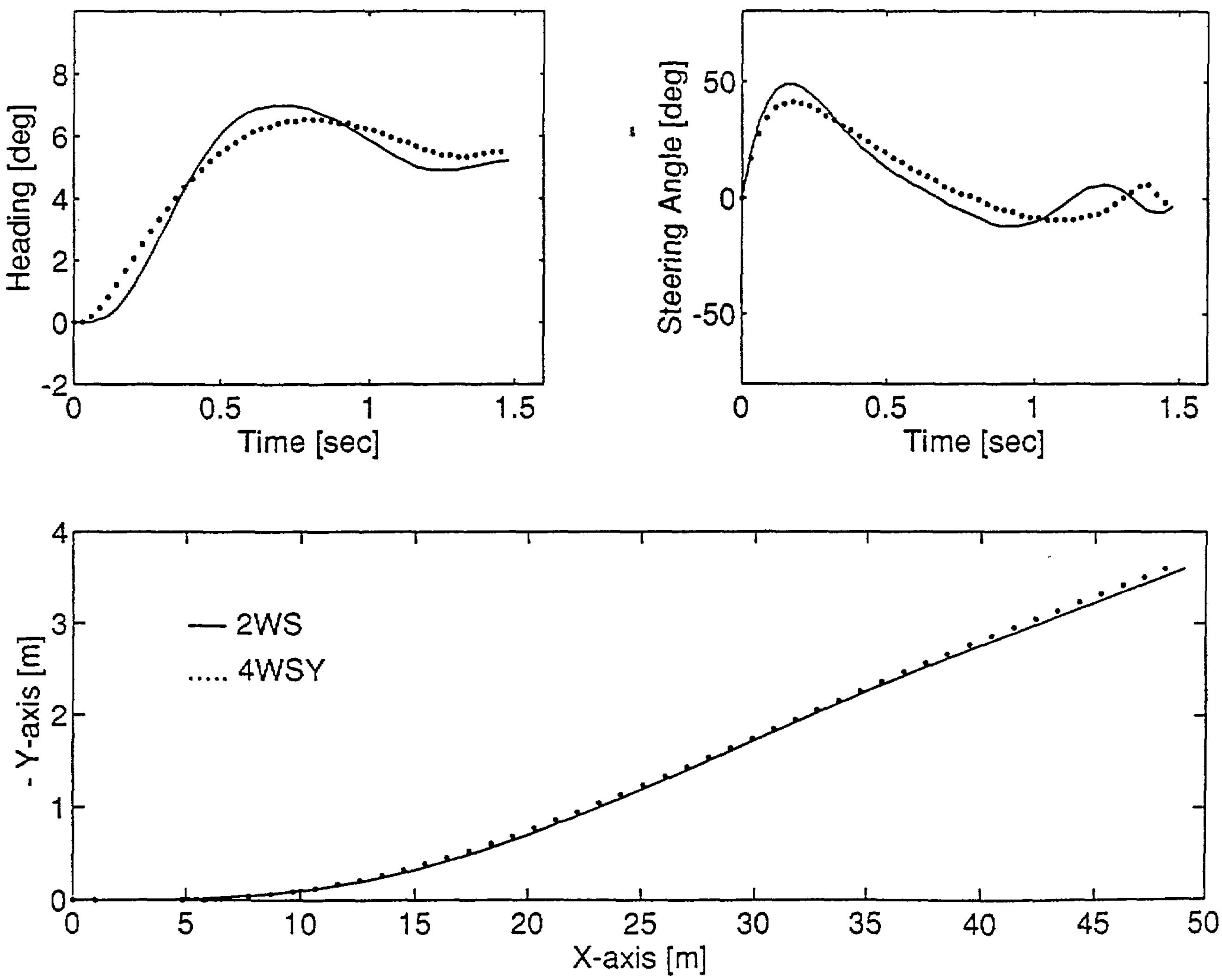

Fig. 8 Comparison of lane change maneuvers (2WS vs 4WSY)