

Speed Choice and Steering Behavior in Curve Driving

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The relation between speed choice and steering performance during curve negotiation was studied in a driving simulator. The hypothesis was that curve radius and steering competence both affect steering error during curve driving, resulting in compensatory speed choice. In this, the control of safety margins was assumed to operate as a regulatory mechanism. Smaller curve radii resulted in a larger required steering wheel angle, and steering error increased linearly with required steering wheel angle. Participants compensated for this by choosing a lower speed, such that the time to line crossing to the inner lane boundary was constant over all curve radii examined. Steering competence was measured during straight-road driving. Poorer steering competence also resulted in larger steering errors, which were compensated for by choosing a lower speed, such that the safety margin to the inner lane boundary was unaffected by steering competence.

INTRODUCTION

Car-driving behavior in curves may be regarded as an interesting case in which steering, as an example of operational performance, is intimately related to behavior on the tactical level—in this case, the choice of speed as a function of curve radius. The distinction between the operational and the tactical level of car-driving behavior has been made by several authors (see Michon, 1985) and might form a fruitful basis for the development of modern driver behavior theories (see Ranney, 1994). Until now, studies of car-driving behavior in curves have focused exclusively on either speed choice or steering behavior, and no attempt has been made to integrate these two lines of research.

A consistent finding in studies of speed choice in curves is that speed has a curvilinear relation to curve radius (see Kanellaidis, Golias, & Efsthadiadis, 1990) and an inverse relation to lateral acceleration. This means that with smaller radii, speed is lower but lateral acceleration is higher than with larger radii (see McLean, 1981). Sometimes an inverse linear relation is reported (Ritchie, McCoy, & Welde, 1968), whereas other studies have found an inverse nonlinear relation between speed and lateral acceleration (Herrin & Neuhardt, 1974; Macura, 1984). These results have encouraged the idea that drivers use lateral acceleration as a cue in speed choice, in that they accept a smaller lateral acceleration as a safety margin at higher speeds (and thus larger radii).

In studies of steering behavior during curve negotiation, speed is usually held constant. Dinges (1978) presented a two-level steering control model that incorporated negotiation of

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DONGES (1978)

curves. Anticipatory open-loop control begins with a steering action some time before the curve is entered; this is followed by a steering wheel angle maximum, δ_{sa} , in the curve. Then a period of stationary curve driving begins, during which the driver generates correcting steering actions in a compensatory closed-loop mode.

In a survey of models of steering behavior, Reid (1983) argued that driver models should incorporate both lane tracking and speed control. In Donges's model the parameters estimated to fit the model on experimental data were influenced by vehicle speed and confounded with road curvature. Curve radius and speed during curve negotiation affect required operational performance because both factors affect the required steering wheel angle.

Godthelp (1986) described this phenomenon as follows: The required steering wheel angle for a particular curve can roughly be characterized as $\delta_{sr} = GL(1 + K\alpha^2)/R_r$. In this, δ_{sr} represents the required steering wheel angle, R_r the road radius in meters, G the steering system gear ratio, L the wheelbase, K a vehicle-related stability factor, and u the longitudinal speed in m/s. For any given speed, required steering wheel angle then increases with smaller radii, but for a given radius, it increases with higher speed, if K is larger than zero, which is the case for a normal understeered car.

If the steering wheel angle during curve negotiation matches the required steering wheel angle perfectly, speed is restricted only by an upper limit at which the vehicle begins to skid. The speed at which this occurs is generally much higher than actual speed in curves. The hypothesis of the present study is that steering errors play an important role in speed choice, such that speed is adapted to operational performance. There is some evidence that steering errors increase linearly with required steering wheel angle (see Godthelp, 1985, 1986). Because negotiating curves with a smaller radius requires a larger steering wheel angle, the implication is that steering error is larger in curves with smaller radii than with wider curves. If steering error is a linear function of required steering

wheel angle, the fraction defined as steering error divided by required steering wheel angle should be constant over radii.

There is also evidence that steering error is affected by steering competence. Cavallo, Brun-Dei, Laya, and Nebojt (1988) found that under visual occlusion, experienced drivers estimated the correct required steering wheel angle better than did inexperienced drivers. Experienced drivers also exhibited less variation in steering wheel amplitude during closed-loop control compared with inexperienced drivers. These results suggest that experienced drivers generate smaller steering errors.

If the driver compensates for larger steering errors induced by smaller radii or poorer steering competence by choosing a lower speed, some regulating mechanism or safety margin is required that determines how speed is adapted. We suggest here that the *time to line crossing* (TLC), developed by Godthelp, Milgram, and Blaauw (1984), is such a safety margin. TLC represents the time available for a driver until the moment at which any part of the vehicle reaches one of the lane boundaries. In a study by Godthelp (1988), drivers were instructed to generate correcting steering actions when vehicle heading could still comfortably be corrected to prevent a crossing of the lane boundary. Drivers made a corrective steering action at a constant TLC irrespective of vehicle speed.

The model of the relation between speed choice and steering performance may then be summarized as follows: Required steering wheel angle is determined by curve radius and speed, whereas steering error is determined by required steering wheel angle and steering competence. It is assumed that the driver has learned the effect of curve radius and speed on required steering wheel angle and on steering error from previous experience. In addition, it is assumed that steering error is consistent and that the driver is aware of his or her steering competence.

When the driver approaches a curve, both radius and steering competence cause an anticipatory adjustment of speed, much like the

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anticipatory avoidance response in the threat-avoidance model of Fuller (1984). The effects of radius and steering competence on steering error are traded off with speed, such that the safety margin TLC remains constant and independent of radius and steering competence. Although mathematically, TLC is determined by steering error as well as speed, the higher steering errors associated with smaller radii and poorer steering competence are assumed to result in lower speeds because of the constancy of preferred TLC as a guiding principle. This principle will then result in low or nonsignificant correlations of speed and steering error with TLC. The relation between lateral acceleration and speed is then assumed to be a by-product of this mechanism.

In the present experiment, steering competence was measured separately during straight-road driving. Road radius was manipulated within subjects, with radii of 40, 80, 120, and 160 m. Originally, lane width was manipulated within subjects as well because it was expected to affect TLC. However, because the effects of lane width are not of crucial importance to the issue addressed here, we will not discuss those effects in this paper. Also, participants used only a part of the lane width because they drove relatively close to the inner lane boundary. This counteracted possible effects of lane width on TLC and speed choice. There is also evidence in the literature that drivers use the inner lane boundary as a reference for vehicle guidance (see Cohen & Studach, 1977; McDonald & Ellis, 1975; Shinar, Rockwell, & Malecki, 1980). Therefore, only TLC and steering behavior data with reference to the inner lane boundary are reported in the present article.

METHOD

Apparatus

The experiment took place in the Traffic Research Centre's fixed-based driving simulator. The equipment consisted of a car (BMW 518) with a steering wheel, clutch, gear, accelerator, brake, and indicators connected to a Silicon

Graphics Skywriter 340VGXT computer. A car model converted driver control actions into a displacement in space. On a 2×2.5 m projection screen placed in front of the car mockup, an image of the outside world with a horizontal angle of 50° was projected by a graphical video projector controlled by the three-dimensional graphics software. Images were presented at a rate of 15 to 20 frames/s, resulting in a suggestion of smooth movement. The visual objects were buildings, roads, traffic signs, traffic lights, and artificially intelligent traffic. The sound of the engine, wind, and tires was presented by means of a digital sound sampler receiving input from the simulator computer. The simulator is described in more detail elsewhere (van Winsum & van Wolfelaar, 1992; van Wolfelaar & van Winsum, 1992).

Procedure

A circuit of two-lane roads with a lane width of 3.0, 3.5, or 4.0 m was used. The roads were delineated with broken center lines and continuous edge lines. Four left-turning curves with 90° angles and radii of 40, 80, 120, and 160 m were separated by straight-road segments.

After completing a questionnaire on driving experience and age, participants practiced driving in the simulator for 10 min. They were instructed to choose their own preferred speed but to adapt the speed for curves as they normally would and to stay in the right lane. There were three trials, one for every lane width. Each trial consisted of five round-trips. This means that in every trial, all four curves were negotiated five times. The three trials are treated here as multiple measurements.

Data Registration and Analysis

Sample measurements (10 Hz) were taken on speed (m/s), lateral position, steering wheel angle (degrees), TLC (seconds), and steering error (degrees).

The steering integral ($I\delta_s$) during straight-road driving was used as a measure for steering competence. This was computed as follows: The steering wheel signal was divided into periods

when the steering wheel was turned to the left and periods when it was turned to the right (relative to the zero angle). For every period, the amplitude was integrated over time, and these integrals were averaged, resulting in $I\delta_s$. Thus this measure is affected by both steering wheel amplitude and frequency. A smaller steering integral represents better steering performance. Steering error in curves, δ_{se} , was defined as the difference between the actual steering wheel angle and required steering wheel angle ($\delta_s - \delta_{sr}$).

Figure 1 presents a time history of steering error and TLC during curve negotiation. The curve is entered at Time 0. Positive values of steering error and TLC represent steering to the inner lane boundary (left) and negative values represent steering to the outer lane boundary (right). The steering error fluctuates around zero. If steering error is zero, then the steering wheel angle equals the required steering wheel angle. The open-loop phase ends when the maximum steering wheel angle (δ_{sa}) is reached. In Figure 1 this is indicated by the first maximum for δ_{se} . This is followed by closed-loop steering control, during which deviations from the required steering error are minimized by the driver. We analyzed the following variables:

- The steering error δ_{se} on the moment (δ_{sa}) is reached. This represents the steering error during the open-loop phase.
- The required steering-wheel angle δ_{sr} . This was

measured as the steering wheel angle at the moment that steering error was zero just before δ_{sa} was reached.

- The steering error ratio, computed as δ_{se}/δ_{sr} . This ratio is a measure for the relative steering error.
- The steering error integral, $I\delta_{se}$, during the closed-loop phase. This was computed as the average integral of all periods when the steering error was directed toward the inner lane boundary.
- The minimum TLCs to the inner lane boundary, TLC_{min} , during the closed-loop phase. These were determined and averaged for every radius-trial combination.
- The minimum speed during curve negotiation. This was determined and averaged for every radius-trial combination.

The effects of radius were analyzed with repeated-measures analysis of variance. The effects of steering competence were analyzed with correlation and regression analyses. The confidence level for significance was set at $p < .05$.

Participants

Sixteen drivers (eight men and eight women) participated in the experiment. The average age was 34 years ($SD = 6.3$, range 22 to 47). They were licensed drivers for 12 years on average ($SD = 6.3$, range 2 to 27). Their average annual kilometrage was 10 594 ($SD = 8267$, range 1500 to 30 000).

RESULTS

The correlation between steering integral $I\delta_s$ and drivers' total kilometrage was -0.62 ($p < .01$). This means that more experienced drivers steered more accurately on straight-road segments.

The minimum speed during curve negotiation was significantly affected by radius, $F(3, 15) = 58.17$, $p < .01$. Required steering wheel angle (δ_{sr}) was significantly affected by radius, $F(3, 15) = 188.24$, $p < .01$, as were steering error (δ_{se}) during the open-loop phase, $F(3, 15) = 28.28$, $p < .01$, and the steering error integral ($I\delta_{se}$) during the closed-loop phase, $F(3, 15) = 14.29$, $p < .01$. The effect of radius on steering error ratio was not statistically significant. Also, the effect of radius on the minimum TLC (TLC_{min}) during the closed-loop phase was not significant. The

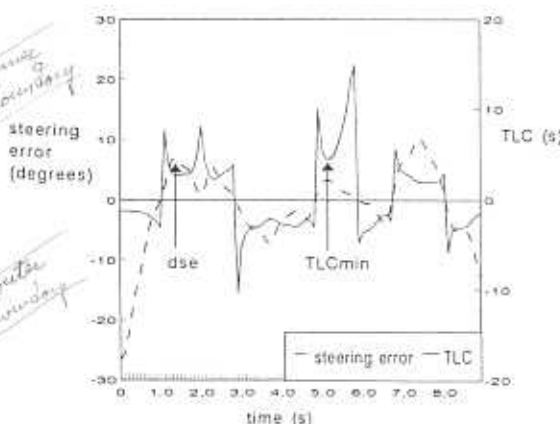


Figure 1. Steering error and time-to-line-crossing time history during curve negotiation ($dse = \delta_{se}$).

averages of these dependent variables as a function of radius are presented in Table 1.

A smaller radius resulted in a larger required steering wheel angle, larger steering errors, and lower speed. However, TLC and the steering error ratio were constant over all radii. Steering errors during both the open- and closed-loop phases were affected by radius in the same manner.

In order to test effects of individual differences in steering competence on dependent variables, these variables must be consistent within the driver. In that case it is justified to average over all measurements (4 radii $\times$ 3 repetitions). In that way the effect of radius is canceled and the effect of individual differences is preserved. The reliability, or consistency, of the dependent variables was tested with the standardized alpha coefficient. This represents the estimated square of the correlation of scores on a collection of items—in this case the 12 measurements—with true scores (Nunnally, 1978). For basic research a reliability of .80 is generally regarded as a satisfactory level. Table 2 presents the standardized alpha coefficients for all dependent variables.

All variables were reliable, and most alphas were higher than .90. The minimum speed, TLC, steering errors, required steering wheel angle, and steering error ratio were averaged over radii and repetitions. Figure 2 presents the results of multiple regression analyses. Only significant partial regression coefficients are displayed.

The measures for steering errors in the open-

TABLE 2

Standardized Alpha Coefficients of Dependent Variables

Dependent Variable	Standardized Alpha
Speed	0.93
Required angle	0.91
Steering error	
open loop	0.88
closed loop	0.86
Steering error ratio	0.91
Minimum TLC	0.90

loop and closed-loop phases are strongly inter-correlated, indicating that they measure the same phenomenon. Steering error is determined by required steering wheel angle, whereas speed affects steering error only indirectly via its effect on required steering wheel angle. Required steering wheel angle is strongly determined by speed. In addition, steering error is strongly determined by steering competence (δ_s). Still, although higher steering competence results in lower steering error, it also results in higher speed.

Because steering competence is an intermediary factor, there is no effect of speed or steering error on TLC. In addition, steering competence does not affect TLC. This suggests that drivers with poorer steering performance maintain the same safety margin as those with better steering performance and that the former choose a lower speed in order to maintain that safety margin. The correlation between δ_s and steering error ratio was 0.74 ($p < .01$).

DISCUSSION

The effects of curve radius as a road design factor and steering competence as an individual driver characteristic on speed choice in curves were studied from the perspective that effects on operational performance are compensated for on the tactical level. The implied mechanism in the case of curve negotiation is that both curve radius and steering competence affect steering errors at the operational level. In

TABLE 1

Averages of Dependent Variables as a Function of Radius

Dependent Variable	Radius (m)			
	40	80	120	160
Speed (m/s)	11.23	14.92	17.58	17.99
Required angle (degrees)	121.44	74.64	56.56	43.47
Steering error				
Open loop (degrees)	14.20	7.47	5.54	4.75
Closed loop (integral)	14.02	6.55	5.25	4.67
Steering error ratio	0.12	0.10	0.10	0.11
Minimum TLC(s)	2.52	2.70	2.89	2.79

*Reliability across Repetitions
(within Subject)*

*but what
would
happen
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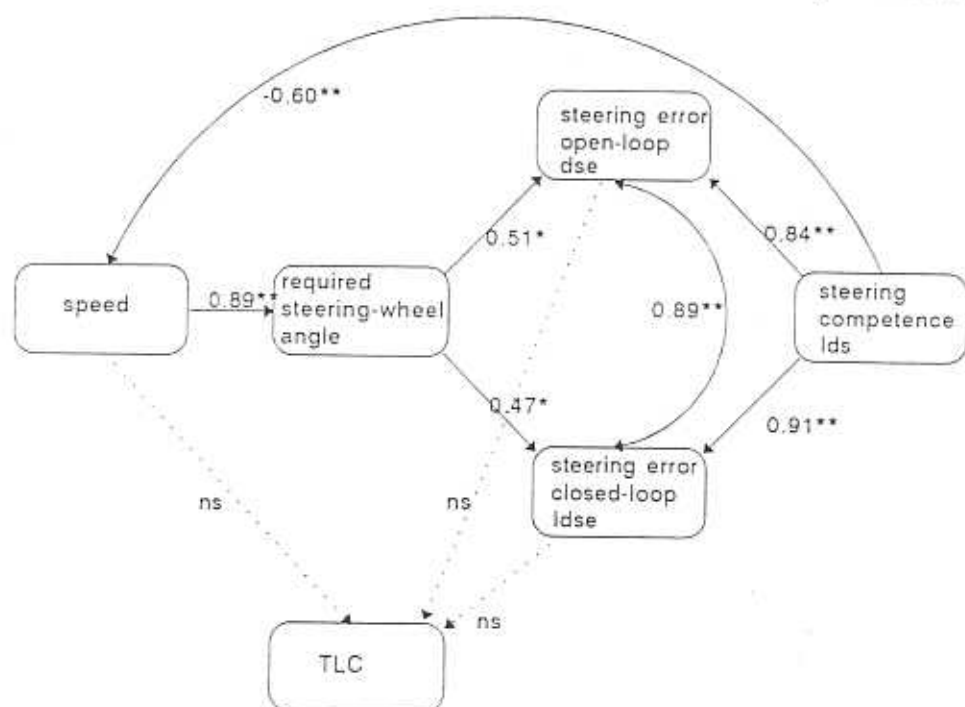


Figure 2. Path diagram with partial regression coefficients (* $p < .05$; ** $p < .01$; ns = not significant; TLC = time to line crossing).

this we assumed the preferred TLC to be a regulating mechanism that determines how speed is controlled in order to compensate for larger steering errors. Because TLC is mathematically determined by speed and steering error, drivers can compensate for higher steering errors by choosing a lower speed, such that TLC is unaffected by radius or steering competence.

The results supported this model. We found that both required steering wheel angle and steering error during the open- and closed-loop phases increase with smaller radii but that the relative steering error, defined as steering error divided by required steering wheel angle, is constant over radii. This strongly suggests that steering error is linearly related to required steering wheel angle and is consistent with the results of Godthelp (1985, 1986).

Smaller radii resulted in the choice of a lower speed, but the minimum TLCs during curve negotiation were not affected by radius. This suggests that drivers compensate for larger steering errors by choosing a lower speed, such that a

constant minimum TLC is maintained. This finding confirms the ideas of Summala (1988) and Rumar (1988) that drivers control safety margins that can be operationalized as distance- or time-related measures. The TLC as a safety margin, then, is controlled by the driver's speed choice. The results suggest that speed choice and steering performance are both intimately related in negotiating curves.

In this study individual differences in steering competence strongly determined speed choice and steering performance in curves. Steering competence was measured with the steering integral during straight-road driving. A larger steering integral is an indication of poorer steering performance. The quality of steering performance was related to driving experience. Steering performance, speed choice, and minimum TLC were consistent within drivers, such that, for example, drivers consistently have a certain level of steering performance during curve negotiation. Steering error was determined both by steering competence and by required steering

wheel angle, whereas required steering wheel angle was determined by speed.

This confirms the model discussed in the introduction. Because drivers with poorer steering performance drove slower, although their steering errors were larger, we found no significant relations of speed and steering errors with TLC. This suggests that drivers with poorer steering competence compensated for their larger steering errors, having a lowering effect on TLC, by choosing a lower speed, which increased TLC. Because steering competence did not affect TLC, it cannot be concluded that drivers with poorer steering competence were less safe drivers. Steering error ratio correlated significantly with steering competence as measured by the steering integral. The strong effect of steering competence on the steering errors during curve negotiation suggests that the steering integral is a good indicator of the quality of steering performance and that steering performance is consistent within the driver.

Based on the finding that steering error is a linear function of required steering wheel angle and on the constancy of the minimum TLC to the inner lane boundary, the speed in curves as a function of radius was calculated using a mathematical model. From this lateral acceleration was computed. Lateral acceleration proved to be an inverse function of speed as a by-product of the presented driver strategy.

Thus it appears that both radius as a road design element and steering competence as a driver characteristic exercise their influence on driving behavior in the same manner. Both affect operational performance, resulting in an adaptation of behavior at the tactical level in an attempt to control safety margins. This is of theoretical significance for driving modeling in general because it suggests that effects of various factors related to the vehicle, weather, road, traffic, temporary states, and the driver on behavior at the tactical level (e.g., speed choice) may exercise their influence via an effect on operational performance. Most driver models are exclusively directed at either the operational or

the tactical level. However, we suggest that the relation between operational performance and behavior at the tactical level should be a fundamental element in driver modeling.

REFERENCES

- Cavallo, V., Brun-Dei, M., Laya, O., & Neboit, M. (1988). Perception and anticipation in negotiating curves: The role of driving experience. In A. G. Gale, M. H. Freeman, C. M. Haslegrave, P. Smith, & S. P. Taylor (Eds.), *Vision and vehicles II* (pp. 365-374). Amsterdam: Elsevier.
- Cohen, A. S., & Studach, H. (1977). Eye movements while driving cars around curves. *Perceptual and Motor Skills*, 44, 683-689.
- Donges, E. (1978). A two-level model of driver steering behavior. *Human Factors*, 20, 691-707.
- Fuller, R. (1984). A conceptualization of driving behaviour as threat avoidance. *Ergonomics*, 27, 1139-1155.
- Godthelp, J. (1985). Precognitive control: open- and closed-loop steering in a lane-changing manoeuvre. *Ergonomics*, 28, 1419-1438.
- Godthelp, J. (1986). Vehicle control during curve driving. *Human Factors*, 28, 211-221.
- Godthelp, J. (1988). The limits of path error-neglecting in straight lane driving. *Ergonomics*, 31, 609-619.
- Godthelp, J., Milgram, P., & Blaauw, G. J. (1984). The development of a time-related measure to describe driving strategy. *Human Factors*, 25, 257-268.
- Herrin, G. D., & Neuhardt, J. B. (1974). An empirical model for automobile driver horizontal curve negotiation. *Human Factors*, 16, 129-133.
- Kanellaidis, G., Golias, J., & Efstathiadis, S. (1990). Drivers' speed behaviour on rural road curves. *Traffic Engineering & Control*, 31, 414-415.
- Macura, D. (1984). *Psychological factor in dimensioning of the horizontal road curves*. Beograd, Yugoslavia: Via Vita, Association of the Road Societies of Yugoslavia.
- McDonald, B. L., & Ellis, N. C. (1975). Driver workload for various turn radii and speeds. In *TRR 530, Driver performance studies* (pp. 18-30). Washington, DC: Transportation Research Board.
- McLean, J. (1981). Driver speed behaviour and rural road alignment design. *Traffic Engineering & Control*, 22, 208-211.
- Michon, J. A. (1985). A critical view of driver behavior models. What do we know, what should we do? In L. Evans & R. Schwing (Eds.), *Human behavior and traffic safety* (pp. 485-520). New York: Plenum.
- Nunnally, J. C. (1978). *Psychometric theory*. New York: McGraw-Hill.
- Ranney, T. A. (1994). Models of driving behavior: A review of their evolution. *Accident Analysis & Prevention*, 26, 733-750.
- Reid, L. D. (1983). A survey of recent driver steering behavior models suited to accident studies. *Accident Analysis & Prevention*, 15, 23-40.
- Ritchie, M. L., McCoy, W. K., & Welde, W. L. (1968). A study of the relation between forward velocity and lateral acceleration in curves during normal driving. *Human Factors*, 10, 255-258.
- Rumar, K. (1988). Collective risk but individual safety. *Ergonomics*, 31, 507-518.
- Shinar, D., Rockwell, T. H., & Malecki, J. A. (1980). The effects of changes in driver perception on rural curve negotiation. *Ergonomics*, 23, 263-275.

- Summala, H. (1988). Risk control is not risk adjustment: The zero-risk theory of driver behaviour and its implications. *Ergonomics*, 31, 491-506.
- van Winsum, W., & van Wolfelaar, P. C. (1992). GIDS small world simulation. In J. A. Michon (Ed.), *Generic intelligent driver support system* (pp. 175-191). London: Taylor & Francis.
- van Wolfelaar, P. C., & van Winsum, W. (1992). A new driving simulator including an interactive intelligent traffic environment. In *Proceedings of the 3rd International Conference on Vehicle Navigation & Information Systems* (pp. 499-506). Piscataway, NJ: IEEE Service Center.
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