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Lane change manoeuvres and safety margins

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Abstract

The relation between perceptual information and the motor response during lane-change manoeuvres was studied in a fixed-based driving simulator. Eight subjects performed 48 lane changes with varying vehicle speed, lane width and direction of movement. Three sequential phases of the lane change manoeuvre are distinguished. During the first phase the steering wheel is turned to a maximum angle. After this the steering wheel is turned to the opposite direction. The second phase ends when the vehicle heading approaches a maximum that generally occurs at the moment the steering wheel angle passes through zero. During the third phase the steering wheel is turned to a second maximum steering wheel angle in opposite direction to stabilize the vehicle in the new lane. Duration of the separate phases were analysed together with steering amplitudes and Time-to-Line Crossing in order to test whether and how drivers use the outcome of each phase during the lane change manoeuvre to adjust the way the subsequent phase is executed. During the first phase the time margin to the outer lane boundary was controlled by the driver such that a higher speed was compensated for by a smaller steering wheel amplitude. Due to this mechanism the time margin to the lane boundary was not affected by vehicle speed. During the second phase the speed with which the steering wheel was turned to the opposite direction was affected by the time margins to the lane boundary at the start of the second phase. Thereafter, smaller minimum time margins were compensated for by a larger steering wheel amplitude to the opposite direction. The results suggest that steering actions are controlled by the outcome of previous actions in such a way that safety margins are maintained. The results also suggest that visual feedback is used by the driver during lane change manoeuvres to control steering actions, resulting in flexible and adaptive steering behaviour. Evidence is presented in support of the idea that temporal information on the relation between the vehicle and lane boundaries is used by the driver in order to control the motor response. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Lane changing; TLC; Safety margins

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1. Introduction

There is evidence that the perception of time margins to objects in the path of the vehicle plays an important role in several parts of the driving task. How a driving subtask is executed depends on the time available before an object is reached or hit. For lane keeping, larger steering errors result in smaller Time-to-Line-Crossing (TLC) to the lane boundaries with constant vehicle speed. The TLC represents the time available for a driver until any part of the vehicle reaches one of the lane boundaries (Godthelp, Milgram & Blaauw, 1984). For curve negotiation, Van Winsum and Godthelp (1996) presented evidence that speed choice depends on the magnitude of steering errors, defined as the difference between actual and required steering wheel angle. The driver compensates poorer steering performance, indicated by larger steering errors, by choosing a lower speed which counteracts the effect of steering error on TLC. The minimum time to the inner lane boundary then operates as a safety margin the driver does not wish to exceed. Van Winsum and Godthelp demonstrated the same principle for the effect of curve radius on drivers' speed choice. Negotiating curves with smaller radii requires a larger steering wheel angle. Since steering error increases linearly with required steering wheel angle (Godthelp, 1985), road radius affects steering wheel error. As a result, negotiating curves with smaller radii generally results in larger steering errors compared to roads with larger radii. Drivers compensate larger steering errors that occur at smaller radii by choosing a lower speed such that TLC to the inner lane boundary is not affected by road radius or vehicle speed.

For the subtask of braking for a decelerating lead vehicle there is also evidence to support that time margins affect the way the subtask is executed. The initiation and control of braking are affected by Time-to-Collision (TTC) at the moment the lead vehicle starts to brake (Van Winsum & Heino, 1996). This supports the idea that drivers use TTC information for judging the moment to start braking and in the control of braking. The TTC is the time required for two vehicles to collide if they continue their speed and remain on the same path (Van der Horst, 1990). Van Winsum and Brouwer (1997) found evidence that TTC to the lead vehicle strongly affects the speed at which the driver moves the foot to the brake pedal. Thus, how the braking response is executed is very much dependent on the time margin or safety margin to the lead vehicle's rear bumper. If the safety margin is smaller, the correcting action by the driver is faster. This was confirmed by the results of Van Winsum (1998) who also presented evidence that drivers who are less able to perceive differences in the TTC to the lead vehicle compensate for this by following other vehicles at a larger distance.

These results support the idea that dynamic subtasks of driving are performed in a flexible manner. Drivers perceive and use rapidly changing temporal information while performing these tasks. The same kind of mechanisms may then control the way lane change manoeuvres are executed. However, steering control during obstacle avoidance and lane change manoeuvres has been described as rigid and inflexible. Summala (1985) has described the steering manoeuvre to avoid an obstacle as a well-learned manoeuvre in which drivers use simple cues to produce stereotypical responses. Also, lane changes have been referred to as steering control actions that require little visual feedback because they use well learned motor programs (Godthelp, 1985).

Summala (1981a) measured the steering response of non-alerted drivers to opening a car door near the vehicle path. After detection of the obstacle, drivers responded in the same manner independent of the distance from the obstacle. This was interpreted as evidence for the inflexibility of the steering response to avoid an obstacle. A similar result was obtained in another study by Summala (1981b). Reid, Solowska and Billing (1981) studied lane changes in a simulator. At varying previews (1.6–3.3 s) a pole came down on the right lane. From that moment the subjects were required to initiate a lane change. In the short preview condition drivers did not respond by moving the steering wheel faster to the left, although the situation was more critical. This suggests that the perception of time-related safety margins does not affect the way the steering response is performed. Alternatively, both levels of preview may have been sufficiently small to urge drivers to respond immediately. Similar results were found by Käppler (1986). The effect of two different types of vehicle dynamics on a double lane change manoeuvre was studied in a simulator. The rear of a truck was displayed in the right lane at a preview of 3 s. This urged subjects to perform a lane change. The time it took to turn the steering wheel to the left was not affected by vehicle speed, vehicle dynamics or lane width. However, vehicle speed did affect steering wheel amplitude: a larger speed resulted in a smaller steering wheel amplitude. This suggests that the duration of the initial steering response is rather inflexible or habitual but steering amplitude depends on vehicle speed. This may be the result of learning the effect of vehicle speed on required steering wheel amplitude. The steering response during lane changing was studied in more detail by Godthelp (1985). The effect of visual occlusion on steering performance was tested in order to evaluate the dependence on visual feedback. Subjects made three series of 60 lane changes from the right to the left lane. The series differed only in vehicle speed. During this manoeuvre the steering wheel angle is first moved to a maximum to the left. After this the steering wheel is moved back to the central position which is reached at about the moment of maximum heading angle. Then the steering wheel is moved to the right until a second maximum is reached. Both steering wheel angles to the left and to the right were smaller at higher speed. This suggests that the driver has learned the required steering wheel angle as a function of speed. However, timing and steering amplitudes were little affected by occlusion. Therefore, it was suggested that a temporary withdrawal of visual feedback has no dramatic effects on a pre-programmed task such as a lane change. Alternatively, the large number of lane changes under similar and predictable circumstances may have resulted in highly trained and predictable lane change manoeuvres that did not require much visual feedback. In contrast, during everyday driving lane changes are performed under widely varying circumstances of lane width and vehicle speed. These factors may affect the way a lane change manoeuvre is performed and may require the use of visual feedback during the lane change.

In summary, the results of studies on lane change behaviour suggest that the manoeuvre is highly trained, inflexible and independent of visual input while, in contrast, the results of behavioural studies of other subtasks suggest that the perception of time margins while performing a manoeuvre affects the way the subtask is executed, resulting in flexible and adaptive performance. On the other hand, most studies on lane changing performance required the subjects to change lanes when there was little time left before an object in front of the car was hit. In these cases, lane changes had to be executed immediately and quickly which may have resulted in stereotypical and inflexible manoeuvres. Another point is that most studies have established that the *duration* of particularly the first phase of the lane change manoeuvre is inflexible and not affected by varying circumstances. This does not prove that the lane change manoeuvre as such is inflexible or that it constitutes a fixed motor programme that is executed independent of visual input during the manoeuvre. In order to clarify this apparent contrast, the experiment reported here tested how drivers adjust the steering response during a lane change manoeuvre under different conditions of vehicle speed, lane width and direction of movement while they are free to execute the lane change manoeuvre in the way they prefer. This resembles the case when, for example, a slower driving lead-vehicle is approached under conditions of good visibility and sufficient distance to change lanes in order to overtake. This constitutes a case of self-paced lane changing in contrast to the forced-paced lane changes in a number of previous experiments. The lane change is initiated by the driver by turning the steering wheel to a certain maximum amplitude. Although drivers have learned the effect of various factors such as road friction, lane width, vehicle speed, on vehicle dynamics and required steering wheel angle, the outcome of the initial steering action on safety margins cannot be completely predicted by the driver. TLC to the outer boundary of the lane the vehicle is moving to was studied as the time-related safety margin. A more critical outcome of the steering action, in terms of a smaller TLC, may then result in a compensatory faster subsequent action. Since the lane change manoeuvre consists of a number of sequential phases these compensatory mechanisms may be operating at each phase. It was investigated whether and how the driver uses the outcome of each phase to adjust the way the subsequent phase is performed. The present experiment was performed in a fixed-base simulator on the assumption that lane changes are mainly initiated and controlled by visual instead of proprioceptive information. However, this assumption needs to be tested in further research.

2. Method

2.1. Apparatus

The experiment was performed in the driving simulator of the Centre for Environmental and Traffic Psychology. The simulator consists of a car (a BMW 518) with a steering wheel, clutch, gear, accelerator, brake and indicators connected to a Silicon Graphics Skywriter 340 VGXT computer. A car model converts driver control actions into a displacement in space. On a projection screen, placed in front, to the left and to the right of the subject, an image of the outside world from the perspective of the driver with a horizontal angle of 150° is projected by three graphical video-projectors, controlled by the graphics software of the simulator. Images were presented with a rate of 20 frames/s, resulting in a suggestion of smooth movement. The sound of the engine, wind and tires is presented by means of a digital sound sampler that receives input from the simulator computer. The simulator is described in more detail elsewhere (Van Wolffelaar & Van Winsum, 1994). The experiment was performed in the simulator because this was the only practical means to systematically investigate the effects of the manipulated factors on lane change behaviour and to measure the required dependent measures.

2.2. Subjects

Eight experienced drivers participated in the experiment. All were between 25 and 50 yr of age. Each had held a driving licence for at least 5 yr while the minimum annual kilometrage was 5000 km. Two were female and six were male.

2.3. Procedure

Two-lane roads with an emergency lane on the right side of the driving lanes were used. All roads had broken centre lines and continuous edge lines. The lane width of all lanes, including the emergency lane was either 3.1 or 3.5 m. The subjects had already driven in the simulator for about 30 min before the experiment started and thus were sufficiently practised. Lane changes were trained by performing a number of practice trials. During the experiment subjects were instructed to drive with a constant speed of either 50, 80 or 120 km/h. During the experiment all subjects performed a number of lane change manoeuvres. Subjects were prompted by the experimenter to initiate the lane change and they were instructed to execute the manoeuvre as they would do normally in similar circumstances on the road. Only lane changes on straight road sections are analysed and discussed here. The following factors were varied: lane width (3.1 or 3.5 m.), vehicle speed (50, 80 or 120 km/h) and direction (for each trial 2 to the left and 2 to the right). All conditions were replicated which resulted in 48 lane changes for every subject. In every trial four lane change manoeuvres were performed in the following order: from the right to the left lane (direction left), from the left lane to the right lane (direction right), from the right lane to the emergency lane (direction right), from the emergency lane to the right lane (direction left). After this, the lane changes were repeated under the same conditions (replication). Then subjects were instructed to increase speed to the next higher level, i.e. from 50 to 80 km/h or from 80 to 120 km/h and the same series of lane changes was repeated.

2.4. Data registration and analysis

Fig. 1 represents a time history of a lane change from the right to the left lane. It shows that the steering wheel is first turned to the left (positive angle) and then to the right (negative angle). Thereafter, the steering wheel is moved back to the initial position. The manoeuvre was divided into three phases for analytical purposes. The first phase starts at t_0 when the steering action is initiated and ends at t_{s1} when the steering wheel is turned to the maximum δ_{s1}. T1 is the duration of the first phase. Next, the steering wheel is turned to the opposite direction. At about the moment the steering wheel angle passes the neutral position the maximum vehicle heading ψ_m is reached at t_ψ. T2 is the duration of the second phase. Next, the steering wheel is turned to the second maximum δ_{s2}. The duration of the third phase, T3, is the interval between t_{s2} and t_ψ. Between t_{s1} and t_{s2} TLC to the outer boundary of the lane the vehicle is moving to decreases until a definite minimum is reached. In practice, the time at which the minimum TLC is reached is difficult to determine because usually TLC decreases until it remains approximately constant for some time.

Steering wheel angle and lateral position were sampled with a frequency of 10 Hz. Lateral position was measured as the distance between the middle of the front bumper and the right edge-line of the road. It was used to compute TLC to the outer lane boundary of the lane the driver was moving to. Thus, if the subject performed a right to left lane change, TLC was computed to the left edge line of the left lane. If the subject was moving from the left to the right lane TLC was computed to the right edge line of the right lane, and so on. TLC was computed as the lateral distance to the lane edge (between the front wheel of the vehicle that is closest to the lane edge and the edge line) divided by the sum of first and second derivative of lateral position. This method,

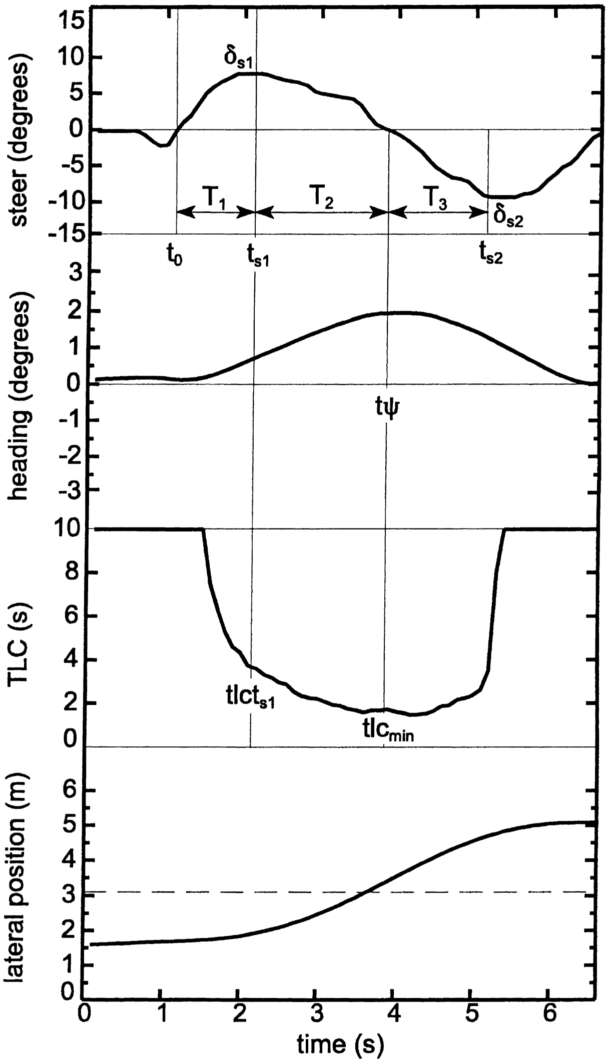

Fig. 1. Time history of a lane change manoeuvre. Example from one subject.

discussed in Van Winsum, Brookhuis and De Waard (1998) gives accurate and reliable approximations of TLC. The TLC at the moment of first steering wheel maximum (TLC_{ts1}) and minimum TLC (TLC_{min}) were analysed.

Two types of statistical analyses are reported here. For the analyses of variance, the means of the duration of the three phases separately, the maximum steering wheel angles and TLC were computed for each level of the factors lane width (2 levels), vehicle speed (3 levels) and manoeuvre (4 levels) for each subject. The values for the two trials in each condition were averaged. The means were tested with a repeated measures within-subjects design. Secondly, (Pearson) correlation and regression analyses were applied on the z-scores that were computed for the relevant dependent variables for each subject separately. By this procedure, the effects of individual differences in the magnitude of the variables are cancelled. With these analyses it was tested whether subjects adapted the motor response to perceptual input during the consecutive phases of the lane change. Each phase was treated as a sequence of *input* that is used by a *process* to arrive at a *result*. In this, the result of the previous phase is the input for the next phase. In the analyses that follow three consecutive phases are examined in detail. For the first phase it was tested whether speed affects both the first steering wheel maximum and TLC at the moment of first steering maximum. The driver may generate a smaller initial steering wheel amplitude if speed is higher in order to control the safety margin TLC_{ts1}. In that case, the partial regression coefficient β of speed on TLC_{ts1}, with the effect of δ_{s1} controlled for, is expected to be higher compared to the Pearson correlation coefficient. For the second phase it was tested whether a smaller TLC_{ts1} results in a compensatory smaller T2 in order to prevent a smaller minimum TLC. The partial regression coefficient of TLC_{ts1} on TLC_{min}, with the effect of T2 controlled for, then is expected to be higher than the correlation between the two TLCs. For the third phase the effects of TLC_{min} and speed on the second steering wheel maximum δ_{s2} were tested. A more critical TLC_{min} may be compensated by a larger steering wheel angle to the opposite direction. Statistical significance was set at the .05 level.

3. Results

3.1. Analyses of variance

The duration of the initial steering action (T1) and the duration of the second phase (T2) were not significantly affected by any of the factors lane width, vehicle speed or direction of movement. The duration of the third phase, T3 was only significantly affected by the factor direction, $F(1,7) = 7.14$, $p < 0.05$ (1.22 s for manoeuvres to the left and 1.14 s for manoeuvres to the right). This effect is difficult to interpret: the difference is only significant for the right to left lane (movement to left) and the left to right lane (movement to right) manoeuvres but not for the other two.

The first steering wheel maximum δ_{s1} was significantly affected by speed, $F(2,14) = 44.46$, $p < 0.01$, but not by lane width or direction. The effect of vehicle speed on second steering wheel maximum δ_{s2} was significant as well, $F(2,14) = 6.42$, $p < 0.05$, and the effects of lane width and direction were again not statistically significant. The interaction between vehicle speed and first vs. second angle on maximum steering wheel angle was statistically significant ($F(2,14) = 7.72$, $p < 0.01$). Thus, the first steering wheel maximum is affected more by vehicle speed compared to the second steering wheel maximum. Table 1 gives the average steering wheel amplitudes as a function of vehicle speed.

TLC at the moment of first steering wheel maximum (TLC_{ts1}) was not significantly affected by lane width, vehicle speed or direction. This is surprising because normally a smaller TLC is expected with a higher speed. The minimum TLC (TLC_{min}) was significantly affected by speed, $F(2,14) = 15.30$, $p < 0.01$, and by direction, $F(1,7) = 45.82$, $p < 0.01$: a higher speed resulted in a smaller TLC_{min} (50 km/h: 1.74 s; 80 km/h: 1.48 s; 120 km/h: 1.36 s). Lane changes to the left resulted in a smaller TLC_{min} (1.36 s) compared to lane changes to the right (1.70 s).

Table 1
Average steering wheel amplitudes δ_{s1} and δ_{s2} (degrees) as a function of vehicle speed

Steering amplitude	Vehicle speed (km/h)		
	50	80	120
δ_{s1}	14.74	10.73	9.03
δ_{s2}	12.77	10.59	9.70

3.2. Correlation and regression analyses

Fig. 2 gives the results of regression analyses for the first, the second and the third phase of the lane change manoeuvre. For both the dependent and the independent variables z-scores were used. The results are based on a total of 374 cases. There were 8 subjects with 48 cases each. A total of 10 cases were coded as missing because of measurement errors.

3.2.1. First phase

Fig. 2A gives the results of regression analyses with TLC at the end of the first phase as the dependent variable and vehicle speed and first steering wheel maximum (all transformed to z-scores for each subject separately) as the independent variables. The correlation between vehicle speed and TLC_{ts1} is the sum of the direct and the indirect effect of speed on TLC_{ts1}. The direct effect is the partial regression coefficient of speed on TLC_{ts1}, with the effect of δ_{s1} controlled for. The indirect effect of speed is the product of the direct effect of speed on δ_{s1} and the direct effect of δ_{s1} on TLC_{ts1}, i.e. with the effect of speed controlled for. In the figure it can be seen that the effect of vehicle speed on initial steering wheel maximum δ_{s1} is quite strong ($\beta = -0.61$): a higher speed

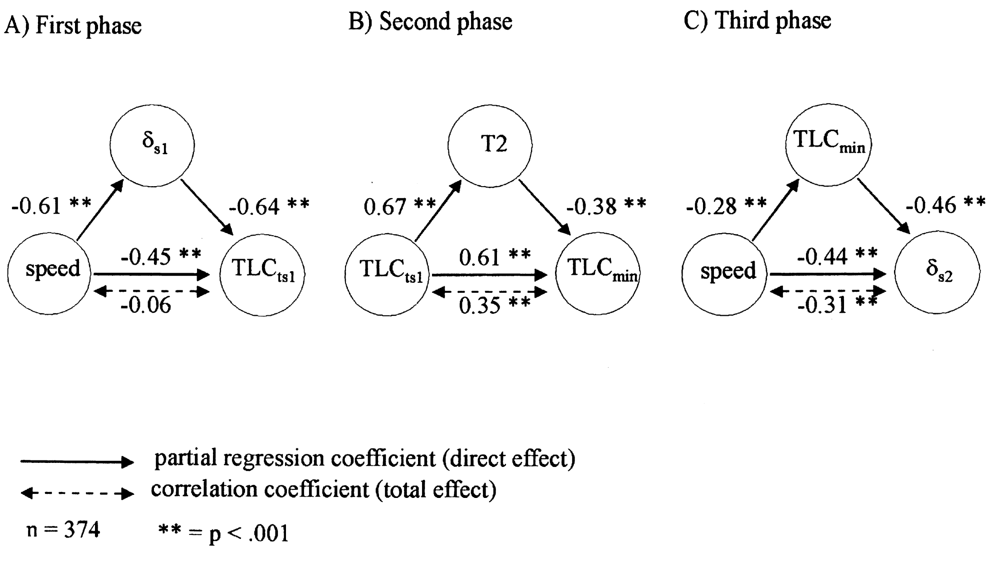

Fig. 2. Regression models of the first, second and third phase of the lane change manoeuvre.

results in a smaller steering wheel maximum, which is consistent with the results of the analyses of variance. Also, the effect of δ_{s1} on TLC_{ts1}, with the effect of speed controlled for, is quite strong ($\beta = -0.64$): a larger steering wheel amplitude, with the effect of speed controlled for, results in a smaller TLC_{ts1}. Thus, a higher speed results in a smaller steering wheel amplitude, and this results in a larger time margin to the lane boundary (TLC_{ts1}). But the direct effect of vehicle speed on the safety margin indicates that the time margin is reduced by a higher speed ($\beta = -0.45$). Together the direct and indirect effects of speed on TLC_{ts1} add up to a non-significant correlation ($r = -0.06$). Thus, the results suggest that adaptation of first steering wheel maximum to vehicle speed may have resulted in the control of the safety margin at the end of this phase, such that a higher speed does not result in a smaller TLC_{ts1}.

3.2.2. Second phase

In the model, TLC at the end of the first phase was treated as the input for the second phase. At the end of the second phase TLC is about at its minimum. It was tested whether TLC_{ts1} affects the duration of the second phase (T2) such that TLC_{min} is controlled by the driver. Fig. 2B gives the results of regression analyses with minimum TLC as the dependent variable and TLC_{ts1} and T2 (all transformed to *z*-scores for each subject separately) as the independent variables. The effect of TLC_{ts1} on T2 is quite strong ($\beta = 0.67$): a higher criticality, indicated by a smaller TLC_{ts1}, at the moment the steering wheel angle is at its maximum, resulted in a faster movement of the steering wheel to the neutral position (smaller T2). The direct effect of TLC_{ts1} on TLC_{min} is considerably larger ($\beta = 0.61$) than the correlation between these two ($r = 0.35$). This suggests that a smaller TLC at the moment of maximum steering amplitude results in a compensatory faster turning of the steering wheel to the neutral position in order to control minimum TLC.

3.2.3. Third phase

TLC is usually infinite at the end of the third phase. It was tested whether a smaller minimum TLC is compensated for by a larger steering wheel amplitude. On the other hand, analysis of variance revealed a significant effect of vehicle speed on TLC_{min}: a higher vehicle speed results in a smaller minimum TLC. This may, however, result in a compensatory larger steering wheel amplitude. Fig. 2C gives the results of regression analyses with the second maximum steering wheel angle as the dependent variable and speed and TLC_{min} (all transformed to *z*-scores for each subject separately) as the independent variables. The steering wheel maximum was significantly affected by TLC_{min}: a smaller safety margin (TLC_{min}) results in a larger compensatory steering wheel amplitude ($\beta = -0.46$). This effect is similar in size to the direct effect of vehicle speed on δ_{s2} ($\beta = -0.44$). Although the direct effect of vehicle speed on δ_{s2} is larger than the correlation, the difference is small. This indicates that the effect of minimum TLC on δ_{s2} suppresses the effect of speed on δ_{s2} but only to a limited degree.

4. Discussion and conclusions

The results of the present experiment suggest that the lane change manoeuvre is executed in a flexible way in which the motor response is adjusted to perceptual input during the lane change manoeuvre. In addition, the evidence presented supports the conclusion that the effect of vehicle speed on steering wheel amplitude that has been reported in the literature, may be a well learned open-loop response that aims at maintaining safety margins at the end of the initial steering action. The results support the hypothesis that the driver performs the driving task in such a way that safety margins are controlled. Lane width did not have a significant effect on any of the dependent variables. If the lane change manoeuvres would have been performed in a fixed manner for all conditions, lane width would have affected the TLCs, such that a smaller lane width would be associated with a smaller TLC.

The effect of vehicle speed on steering wheel amplitudes, obtained in a fixed-based simulator, is in line with findings of field experiments. The effect of speed on the initial steering wheel amplitude confirms the results of Godthelp (1985) and Käppler (1986). A higher speed results in a smaller steering wheel amplitude. The present study suggests that this is a compensatory process in which the time margin to the lane boundary at the end of the first phase is controlled by the driver. This compensatory process is probably the result of learning the combined effects of speed and steering wheel amplitude on safety margins. In accordance with the results of Reid et al. (1981), Godthelp and Käppler, the duration of the initial steering wheel action appears to be inflexible. It is not affected by any of the factors – lane width, speed or direction. This suggests that, although the effect of speed on required steering wheel maximum is learned by practice, the driver turns the steering wheel to the first maximum in a fixed amount of time.

The duration of the second phase, which starts at the first steering wheel maximum and ends at the moment of maximum vehicle heading, was strongly affected by TLC at the start of the phase. Thus, a more critical situation (i.e. a smaller TLC) at the start of the phase resulted in a compensatory faster response. This has a positive effect on minimum TLC. Thus, in the second as well as the first phase, safety margins were controlled for by a compensatory action of the driver.

However, these two compensatory processes could not prevent a significant effect of vehicle speed on minimum TLC. In the third phase, a smaller minimum TLC was followed by a larger second steering wheel maximum. This explains to some degree the difference in effects of speed on the second and the first steering wheel maximum. A higher speed results in a smaller minimum TLC, which by a process of compensation results in a larger second steering wheel maximum. This positive indirect effect of vehicle speed reduces the impact of the negative direct effect of speed on second steering wheel angle.

In conclusion, the results suggest that visual feedback is used during the lane change manoeuvre in order to adjust steering control actions to the outcome of a previous action in such a way that safety margins are controlled. The results suggest that temporal information about the relation between the vehicle and the lane boundaries is used by the driver to control the motor response. Similar relations between perception and action have been demonstrated in other studies for the case of curve negotiation and for braking in response to a decelerating lead vehicle in car-following. The present results extend these findings to the lane change manoeuvre.

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develop an integrated system that will in real time detect driver impairment and undertake emergency handling prior and during the emergency situation.

References

Godthelp, J. (1985). Precognitive control: open- and closed-loop steering in a lane-change manoeuvre. *Ergonomics*, *28*, 1419–1438.

Godthelp, J., Milgram, P., & Blaauw, G. J. (1984). The development of a time-related measure to describe driving strategy. *Human Factors*, *26*, 257–268.

Käppler, W. D. (1986). Using a driving simulator to investigate vehicle handling properties. In: H. P. Willumeit, *Human decision making and manual control* (pp. 89–99). North-Holland: Elsevier Science Publishers.

Reid, L. D., Solowska, E. N., & Billing, A. M. (1981). A systematic study of driver steering behaviour. *Ergonomics*, *24*, 447–462.

Summala, H. (1981a). Driver/vehicle steering response latencies. *Human Factors*, *23*, 683–692.

Summala, H. (1981b). Drivers' steering reaction to a light stimulus on a dark road. *Ergonomics*, *24*, 125–131.

Summala, H. (1985). Modeling driver behavior: a pessimistic prediction? In: L. Evans & R. C. Schwing, *Human behavior and traffic safety* (pp. 43–61). New York: Plenum Press.

Van der Horst, A. R. A. (1990). *A time-based analysis of road user behaviour in normal and critical encounters*. Thesis, Technical University of Delft, The Netherlands.

Van Winsum, W. (1998). Preferred time headway in car-following and individual differences in perceptual-motor skills. *Perceptual and Motor Skills*, *87*, 863–873.

Van Winsum, W., Brookhuis, K., & De Waard, D. (1998). *Approximations of Time-to-Line Crossing (TLC) for real time measurement during car driving*, Report TM-98-B008. Soesterberg, The Netherlands: TNO Human Factors Research Institute.

Van Winsum, W., & Brouwer, W. (1997). Time headway in car following and operational performance during unexpected braking. *Perceptual and Motor Skills*, *84*, 1247–1257.

Van Winsum, W., & Godthelp, H. (1996). Speed choice and steering behavior in curve driving. *Human Factors*, *38*, 434–441.

Van Winsum, W., & Heino, A. (1996). Choice of time-headway in car-following and the role of time-to-collision information in braking. *Ergonomics*, *39*, 579–592.

Van Wolffelaar, P. C., & Van Winsum, W. (1994). A driving simulator for traffic research using a graphical workstation. In: F. J. Maarse, A. E. Akkerman, A. N. Brand, L. J. M. Mulder & M. J. van der Stelt, *Computers in psychology* 5. *Applications, methods and instrumentation* (pp. 218–229). Lisse: Swets and Zeitlinger.