Testing Speed Reduction Designs for 80 Kilometer per Hour Roads with Simulator

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Reduction of driving speeds offers an important opportunity to improve traffic safety on rural 80 km/hr roads. An experimental project in Drenthe was aimed at developing measures to reduce speed effectively without significantly reducing driving comfort at speeds up to 80 km/hr. Some variants of proposed infrastructure measures were tested in a driving simulator before actual application. Experimental conditions consisted of two lane widths (2.75 and 2.25 m) and three experimental layouts of edge strips: one with a continuous profiled road marking, one with small lateral rumble strips every 5 m, and one every 10 m. On entering this edge strip (the 2.75-m lane had a strip of 0.20 m and the 2.25-m lane one of 0.70 m) auditive feedback by means of sound and steering wheel vibration was generated. A conventional 80 km/hr road (lane width 2.75 m) with standard road delineation served as control condition. Some subjects were instructed to drive in a relaxed manner, and the others were instructed to drive as if under time pressure. The results show that the narrow lane width (2.25 m with a 0.70 m edge strip) reduces speed the most and is fairly resistant to effects of adaptation. Moreover, the narrow lane width especially reduces the speeds of drivers under time pressure, implying that in practice speed variance may be reduced. The different layouts of the edge strips reveal relatively small differences in driving behavior. It is concluded that the basic design elements as developed in this project offer a good prospect for reducing driving speeds in practice.

In the Netherlands, rural 80 km/hr roads have the highest accident rates. In general, high speed contributes substantially to these accidents, and, reduction of driving speed may improve traffic safety on 80 km/hr roads. The experimental project Speed Reducing Measures on 80 km/hr roads in Drenthe—Drenthe is one of the 12 provinces in the Netherlands—was started in 1990 for the development and testing of measures that effectively reduce driving speed without significantly reducing driving comfort up to speeds of 80 km/hr. At speeds above 80 km/hr an increasing discomfort is aimed for. Measures to change the road and road environment that result in a natural lower speed choice by the motorist and reduced speed variation among cars will be explored. Measures of this type are well in line with recent developments of sustainable road safety and self-explaining roads (*1,2*).

The basic design elements for 80 km/hr roads were identified and compiled with the help of representatives from the local, regional and national government, research institutes, consultancies, and police (*3*). The design elements were used in a pre-evaluation of some variants of the proposed measures with respect to driving behavior by a driving simulator study. Apart from this study, the pre-evaluation included computer simulations of the effects of some road surface unevenness patterns on vehicle comfort and tire-road contact and a limited testing of the experimental road surface by instrumented vehicles on a road closed to other traffic (*4–6*).

SPEED-REDUCING MEASURES

The literature on determining factors of speed choice was reviewed. Tenkink (*7*) distinguishes several behavioral models, of which the utility model is the most general: speed will be reduced when the risk or discomfort caused by high speed increases. In weighing the pros and cons of high speed, probability and the size of the consequences are important. For example, Tenkink (*8*) found that there was a reduction in speed when a narrow road width was combined with threatening obstacles along the road. Perceptual speed adaptation, uncertainty, and task demand also may play a significant role in drivers' speed choices. Negative consequences of high speed (discomfort, threat) may be effective if they are consistent, real, and if the involved risk is detectable, recognizable, and verifiable. Although an increasing threat, uncertainty, or workload may reduce speed, traffic safety may not necessarily improve (*9*). For each measure to reduce speed, the probability and the consequences of accidents must be assessed as well. Because drivers may react differently to given measures, with a possible increase in speed variance, measures must promote uniform behavior to the greatest extent possible. Furthermore, on a narrow road the visual guidance may be better than on a wide road, resulting in an increase in speed. These considerations resulted in a basic design for 80 km/hr roads (*3*) that consists of four main elements: lane width, edge marking, center marking, and verge reminders.

Lane Width

An important basic assumption in the design is that the net available lane width for drivers is reduced as much as possible. It takes some manoeuvering to make use of the so-called smooth asphalt part of the lane. Deviations from the right course must result in discomfort at speeds above 80 km/hr, but not in unsafe situations. Another constraint is to ensure that heavy vehicles (trucks, buses) are not impeded at speeds up to 80 km/hr. To meet both requirements, a net lane width of smooth asphalt between 2.25 and 2.75 m was proposed, together with a profiled edge marking that makes up a total road width of 6.20 m.

Edge Marking

A second assumption of the basic design is that no excessive visual guidance should be present. Therefore, it was proposed not to imple-

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ment visual edge markings by delineation, but instead to use a tangible one in combination with the additional width needed for heavy vehicles. This edge marking must be designed in such a way that drivers of heavy vehicles do not notice much discomfort, but drivers of passenger cars experience discomfort that increases with speed.

Center Marking

Reducing the visual guidance of the edge markings requires drivers to get their information on the course of the road primarily from the center markings. The center marking must be clearly visible, even during darkness and bad weather, and must represent a unique code for 80 km/hr roads. Therefore, a 0.30-m center line, instead of 0.10 m, with 3-m-long white lines at 9-m spacing is proposed, preferably with a tangible component.

Verge Reminders

In the Netherlands, post-mounted reflectors at a height of 0.60 m every 40 m usually provide visual guidance. To reduce the visual guidance, these roadside reflectors are removed and replaced by so-called verge reminders that are uniquely designed for 80 km/hr roads at 500-m intervals.

In the simulator study, these four basic elements in the road design of 80 km/hr roads are included.

METHOD

Experimental Design

The aim of the simulator study is to gain insight in the functioning of the proposed measures in terms of driving behavior before they are implemented on the road. In general, results from simulator studies with respect to speed choice are well in line with real-world results (*9–10*), and the relative validity is acceptable. However, absolute speed levels should be interpreted with caution because one tends to drive faster in a driving simulator than in the real world.

The independent variables of the simulator-experiment included: instruction, road type, lane width, and edge-stripe configuration. Instruction and road type were varied between subjects, and lane width and edge-stripe configuration within subjects. A standard rural road with conventional delineation, a lane width of 2.75 m, and post-mounted reflectors every 40 m (see Figure 1) served as a control condition.

Instruction

In a previous simulator study on the effects of speed-reducing measures (*10*) two different driving instructions were used:

- *Relaxed*—Subjects are instructed to drive in a relaxed manner as they normally do when they are not in an hurry.
- *Time-pressure*—Subjects are instructed to drive as quickly as the conditions allow without jeopardizing traffic safety, as if they had left late for an important meeting.

A measure has the greatest effect when the speed of faster-driving motorists is reduced. An effect of instruction will clarify this.

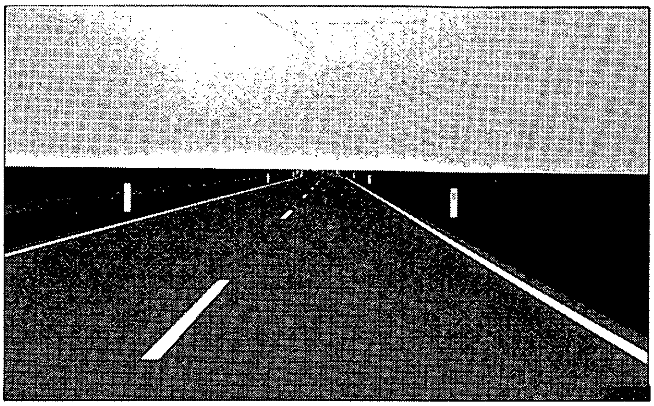

FIGURE 1 Road scene of control 80 km/hr road with conventional delineation in TNO driving simulator.

Road Type

In the experiment two types of rural roads were included:

- *Type A*—A road with long straight sections in an open environment with only a few vertical elements near the road.
- *Type B*—A more winding road through a varied landscape.

Both road types as implemented in the simulator were about 5.5 km long.

Lane Width

Because lane width is an important design element, two lane widths were chosen for the experimental roads: 2.25 m (narrow) and 2.75 m (wide). In all conditions the total road width remained the same, 6.2 m. The narrow lane always had a 0.70 m edge strip to provide enough space for heavy vehicles. All wide lane conditions had an edge strip of 0.20 m. Figure 2 shows the three lane configurations used in this study: the standard 80 km/hr road as a control condition, the narrow lane of 2.25 m, and the wide lane of 2.75 m.

Edge strips

Three experimental edge strip configurations were investigated:

- A continuously profiled marking strip (in the following indicated by profiled). As soon as the right front wheel hits this strip, the driver receives auditive feedback via a loud sound in the vehicle and a vibration in the steering wheel.
- Small cross rumble strips every 5 m. Driving over these rumble strips gives a pulsating sound and vibration in the steering wheel, depending on driving speed (5-m rumble).
- Small cross rumble strips every 10 m (10-m rumble).

These experimental configurations were applied on both edge strip widths (i.e. 0.20 and 0.70 m), resulting in the six experimental conditions shown in Figure 3. The center line of the experimental roads consisted of a 0.30 m-continuous profiled marking, with a series of three white blocks 0.80 × 0.30 m at a mutual distance of 0.30 m every 12 m. Entering the center marking with one of the

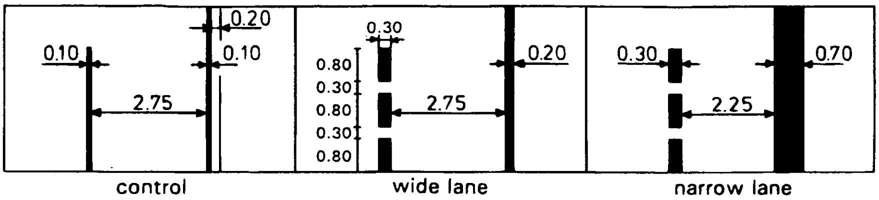

FIGURE 2 Cross section of control road (lane width 2.75 m) and experimental roads with wide (width 2.75 m) and narrow (width 2.25 m) lanes.

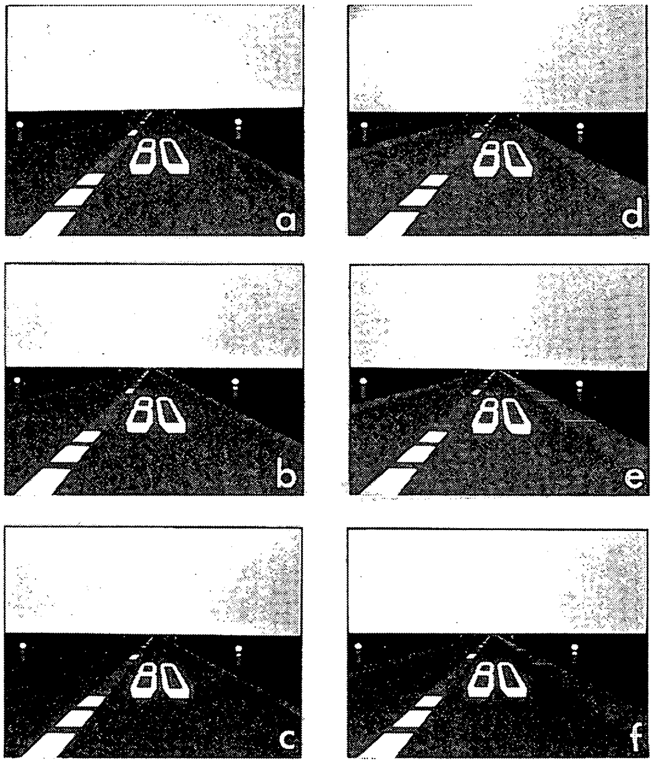

FIGURE 3 Road scenes of six experimental roads with two lane widths (a,b,c wide lane; d,e,f narrow lane) and three edge strip configurations (a and d profiled, b and e 5-m rumble, and c and f 10-m rumble).

wheels results in an auditive feedback to the driver as well. At the beginning of each experimental road the symbol "80" was painted on the road surface (see Figure 3).

To make the control condition comparable with the experimental conditions with respect to the post-mounted reflectors every 40 m, it was decided to have verge reminders every 40 m instead of every 500 m. The verge reminders consisted of red posts with yellow round plates.

Subjects

A total of 32 male subjects participated in the experiment; divided into four (2 × 2: instruction × road type) groups of eight subjects each. They were randomly recruited from the traffic subject records of the TNO Institute for Human Factors (TNO) by driving experience (having a driving license for at least 3 years and driving at least 10,000 km per year), and earlier experience with driving the TNO driving simulator. The ages varied between 21 and 53 years with the average age being 35.5. Subjects were paid for their participation.

TNO Driving Simulator

The experiment was conducted in the fixed-base driving simulator of the TNO. At the time of the experiment, this simulator had a MEGATEK 944 CGI system that generates the visual scene (1024 × 1024 pixels) at a refresh rate of 30 Hz. These images were displayed on a large screen in front of the vehicle mock-up (a Volvo 240) by a high resolution projector BARCOGRAPHICS 800 (*12*). The horizontal visual angle of the projected image was about 50 angular degrees. Recently, the TNO driving simulator has been equipped with a new CGI system and a three channel Evans & Sutherland ESIG 2000 system, which enables a horizontal visual angle of 120 degrees.

Procedure

Before driving in the simulator, subjects got either the relaxed or the time-pressure instruction in written form. Then a test run of about 5 min on a normal 80 km/hr road was begun to get the driver used to driving in the simulator again. In total each subject drove about for 2 hr in the simulator, subdivided into six (2 × 3: lane width × repetition) blocks of about 20 min each. Within each block a subject encountered four roads (control and 3 experimental ones), each road separated from the other by a roundabout at which the driver had to continue straight on. During each block the subject encountered 20 oncoming vehicles at speeds of 80 km/hr. After the experiment subjects completed a brief questionnaire. After a block was finished, a subject alternated with another subject and rested for about 20 min.

Analysis of Driving Behavior

During each run driving speed and lateral position were stored at a sampling rate of 5 Hz. At a sampling rate of 60 Hz where and how long either the center marking or the edge marking was entered by either one of the wheels were stored. Driving behavior on straight road sections and on curves (100 m before and 100 m after the curve included) was analyzed separately. The first and last 500 m of each road were excluded from the analysis. Separate analyses of variance (ANOVAs) were conducted on the dependent variables: speed, standard deviation of speed, lateral position, and standard deviation of lateral position. The number and duration of left and right lane exceedances, as well as the answers on the questionnaire, were analyzed but are reported elsewhere (*13*). The independent variables were instruction (two levels), road type (two), lane width (two), edge configuration (four), and repetition (three). If applicable, only the three experimental edge configurations were included in the ANOVAs.

RESULTS

Speed

The proposed measures aimed at reducing speed. Figure 4 shows the speed, averaged over subject, road type, and repetition, as a function of instruction, lane width ("smooth" asphalt), and the three experimental configurations of the edge strip. The results of the control condition with the conventional 80 km/hr road are added as a reference.

The absolute speed levels appear to be often rather high in a driving simulator. Also in this study, even for the instruction for relaxed driving the absolute speed values are well over 80 km/hr. ANOVA results reveal that differences between subjects contribute most to the variance (56 percent of explained variance). As illustrated in Figure 4, instruction has an important effect on speed. Subjects under time pressure drive about 15 km/hr faster on the straight road sections [113 versus 98 km/hr, F(1,228) = 15.0, $p < 0.001$, 17.3 percent of explained variance] and 14 km/hr faster in curves [110 versus 96 km/hr, F(1,28) = 10.9, $p < 0.005$, 14.3 percent explained variance]. The main effect of lane width does not reach significance [F(1,28) = 3.6, $p < 0.07$]. It appears that under time pressure the speed on the narrow lanes is significantly lower than on the wide lanes (*t*-test, $t = 3.4$, $p < 0.002$). A narrow lane especially reduces the speed of the drivers in a hurry. The three edge strip configurations differ only for the narrow lane width [interaction width × configuration F(2,56) = 7.5, $p < 0.002$]. Combined with the narrow lane width, the configuration with the continuous profiled marking reduces speed somewhat more than the two other configurations. So, the configuration with the most direct feedback to the driver has the most effect on speed. Repetition appears to have a main effect on speed [F(2,56) = 38.3, $p < 0.0001$, 3.1 percent of explained variance]. Speed increases with repetition, but the speed on the narrow lanes increases relatively the least [interaction lane width × repetition F(2,56) = 7.5, $p < 0.002$]. To compensate for this effect of repetition, for each run the difference between the speed on an experimental road and the speed on the control road within the same block has been calculated. Figure 5 gives the results.

An ANOVA reveals a main effect of lane width [F(1,28) = 40.2, $P < 0.0001$, 15 percent of explained variance]. The narrow lane gives the highest speed reduction. Combined with the narrow lane, the edge strip configuration with the continuous profiled marking reduces speed more than the 5 or 10 m rumble [interaction lane width × configuration F(2,56) = 7.5, $p < 0.002$].

To get an idea of the speed variations along a road, for each subject and each road the standard deviation of the speed has been computed separately for straight and curved road sections. Both reveal only main effects of instruction [relaxed 3.23 km/hr versus time pressure 5.54 km/hr, F(1,28) = 22.5, $p < 0.0002$] and repetition [F(2,56) = 11.2, $p < 0.0002$].

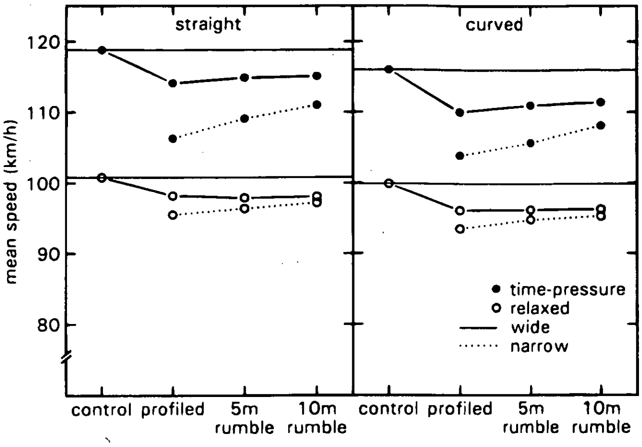

FIGURE 4 Mean speed on straight and curved road sections as function of instruction, lane width, and edge strip configuration.

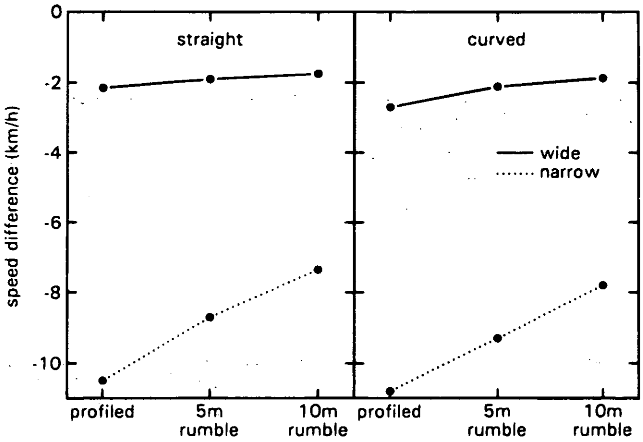

FIGURE 5 Mean difference in speed between experimental and control roads within each block as function of lane width and edge strip configuration on straight and curved road sections.

Lateral Positioning

For each subject the average lateral position relative to the center of the road has been calculated for straight and curved road sections. ANOVAs reveal that neither repetition, instruction, nor edge strip configuration has an effect on lateral position. As can be expected, lane width has far the greatest effect on lateral position [F(1,28) = 509, $p < 0.0001$, 72.9 percent of explained variance]. In the wide lane one drives 1.22 m from the middle of the road, whereas the narrow lane results in a lateral position of 0.99 m (straight road sections). The lane keeping behavior for both lane widths differs significantly from that in the control condition (mean lateral position 1.18 m) (wide lane versus control, $t = 4.04$, $p < 0.001$; narrow lane versus control, $t = 2.58$, $p < 0.02$). The resulting margins left and right of the vehicle relative to the road markings are shown in Figure 6.

With respect to the relative position of the driver within the center and edge strip, the three lanes differ little. On average, the driver chooses a position a little left from the middle of the lane (left 38 percent, right 62 percent).

The standard deviation of lateral position is independent of repetition, instruction, and edge strip configuration. Compared with the

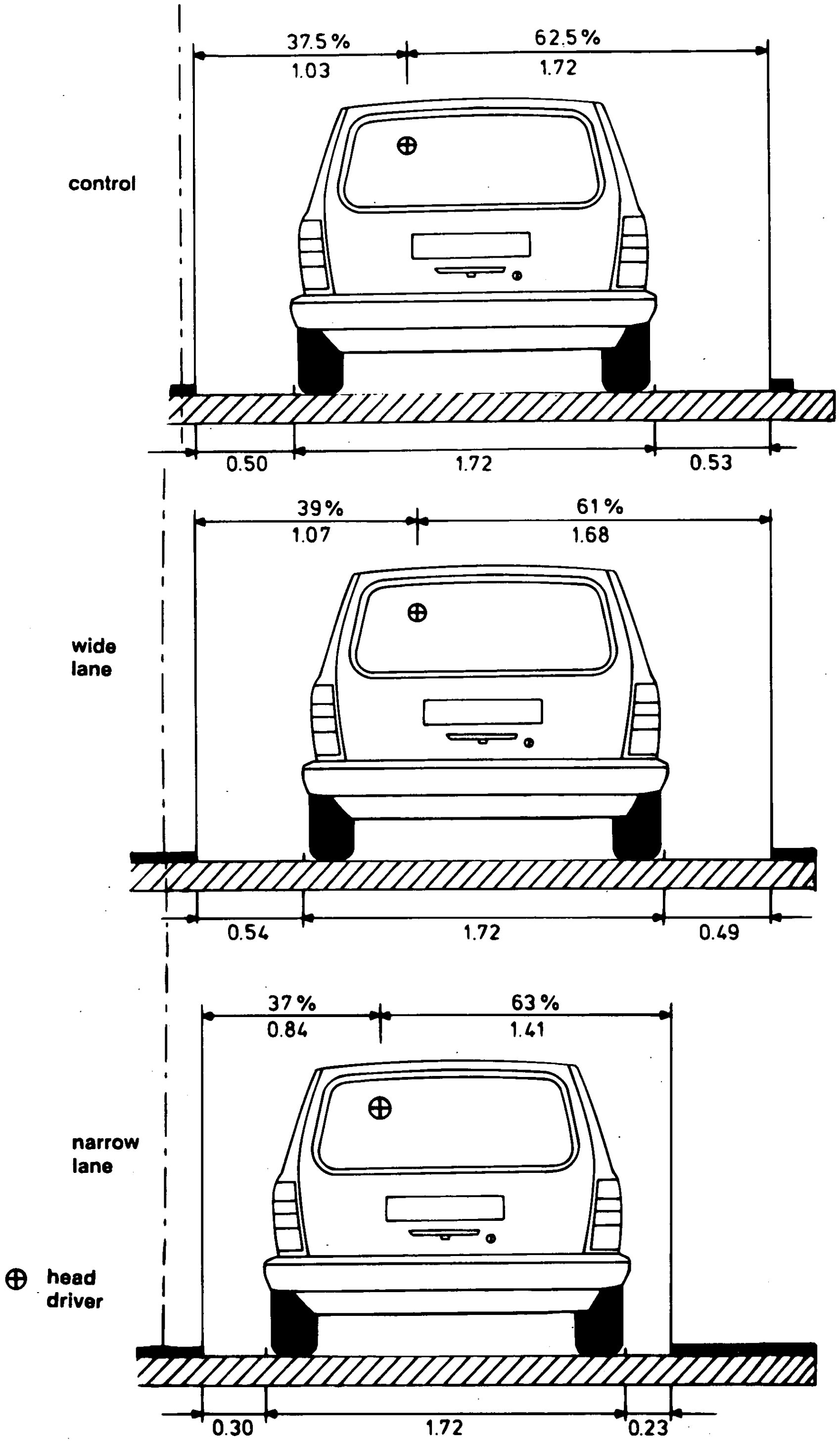

FIGURE 6 Mean lateral position of vehicle and driver within the traffic lane of the control, wide lane, and narrow lane condition.

control condition, the experimental lanes reduce the standard deviation of lateral position [F(3,84) = 52.4, $p < 0.0001$, 18.2 percent of explained variance] with the narrow lane having the strongest effect (standard deviation lateral position on straight road sections on control, wide lane and narrow lane 0.18, 0.15, and 0.12 m, respectively).

DISCUSSION AND CONCLUSIONS

An important question in simulator research is always to what extent the results found in a driving simulator have sufficient validity for actual driving behavior. As indicated before, in general, differences between experimental conditions appear to be comparable with real-world results in terms of relative validity. Absolute speed levels have to be interpreted with caution. This study also makes it clear that drivers drive fast in the simulator. Even with the relaxed driving instruction the driving speeds are well over 80 km/hr. Speed measurements on 80 km/hr roads reveal that the average speed (all vehicles included) is about 77 km/hr (*14*). Two aspects may partly bridge the gap between simulator and real-world results, but certainly not completely. First, about 28 percent of the total number of vehicles on 80 km/hr roads fall into a category of vehicles (vans, trucks, buses) that drive about 10 percent slower than passenger cars. Second, in the current study only free-riding cars were involved, not those influenced by a slower vehicle in front. Bakker and van der Horst (*15*) found that the average speed of free moving vehicles on 80 km/hr roads is about 9 km/hr higher than the average speed of all vehicles. In the current study the authors concentrated on the differences between conditions and especially the effects of the proposed speed reducing measures relative to the behavior on conventional 80 km/hr roads. The experimental configurations with the narrow lane of smooth asphalt of 2.25 m with an edge strip of 0.70 m result in the largest speed reduction relative to the control condition: on average, one drives 9 km/hr slower. With a lane width of 2.75 m (wide lane) only a small speed reduction can be expected. This lane width apparently provides even fast drivers enough space for staying in their lane comfortably. An important result is that the narrow lane especially reduces the speed of the drivers under time pressure. This may imply that in practice speed variance is considerably reduced with positive effects on traffic safety. Moreover, the narrow lane appears to be relatively resistant to effects of adaptation.

Edge strip configuration only has a small effect on speed in the narrow lane conditions. The continuous profiled marking with the most direct feedback to the driver and the greatest discomfort (vibration in the steering wheel and sound) gives the best results. This configuration in practice provides the driver with sufficient feedback. The study of the physical characteristics of different layouts by computer simulations (*4*) shows that the detailed design of the edge strip with the constraint—the discomfort of road users who inevitably have to use the edge strip (heavy trucks, buses) at speeds till 80 km/hr—is only marginal.

The lateral position of the driver within the lane does not differ much among the conditions and is in line with real-world findings of a 40:60 proportion relative to center line and edge line, respectively (*15,16*). In the wide lane condition, the 0.30-m center line with an acoustic warning shifts the driver 0.14 m to the right relative to the standard road profile, resulting in a reduction in the number of center line crossings. In the narrow lane drivers have to choose a lateral position more to the middle of the road, but the number of center line crossings does not increase relative to the control condition. The standard deviation in lateral position decreases for the experimental road designs, the most for the narrow lane and the result of a more accurate steering behavior by the drivers.

In summary, the basic design elements as proposed in this project offer a good prospect for reducing driving speeds in practice successfully. A narrow lane width of smooth asphalt 2.25 m wide, an edge strip of 0.70 m, and a center marking of 0.30 m, with acoustic feedback to the driver when crossing, appear to be effective measures to reduce speed. The final design details of the edge strip have to be based on the evaluation of the physical characteristics by computer simulation (*4*).

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REFERENCES

1. Koornstra, M. J., M. P. M. Mathijssen, J. A. G. Mulder, R. Roszbach, and F. C. M. Wegman. *Naar een duurzaam veilig wegverkeer: Nationale Verkeersveiligheids-verkenning voor de jaren 1990/2010.* Stichting Wetenschappelijk Onderzoek Verkeersveiligheid SWOV, Leidschendam, 1992.
2. Theeuwes, J., and J. Godthelp. *Begrijpelijkheid van de weg.* Rapport IZF 1992 C-8, Instituut voor Zintuigfysiologie TNO, Soesterberg, the Netherlands, 1992.
3. Heidemij. *Proefproject snelheidsbeperkende maatregelen op 80 km-wegen: Schetsboek basisontwerp 80 km-wegen.* Heidemij Adviesbureau bv, Assen, 1992.
4. Hoogvelt, R. B. J., and S. T. H. Jansen. *Oneffenheden in de kantstrook van 80 km/h wegen in Drenthe als fysieke maatregel om de rij-snelheid te beperken.* Rapport 92.RAS.81.1/BH, Instituut voor Wegtransportmiddelen TNO, Delft, the Netherlands, 1992.
5. Steyvers, F. J. J. M., D. de Waard, M. Jessurun, A. J. Rooijers, and K. A. Brookhuis. *Een voorstudie naar de effecten van snelheidsbeperkende maatregelen op het rijgedrag op 80-km wegen.* Rapport VK-92-05, Verkeerskundig Studiecentrum, Rijksuniversiteit Groningen, Haren, 1992.
6. Vos, J., F. W. M. Geurtsen, and A. R. A. van der Horst. *Geluide-missiespectra van twee voertuigen rijdend over een onderbroken steenslagstrook.* Rapport IZF 1992 C-31, Instituut voor Zintuigfysiologie TNO, Soesterberg, the Netherlands, 1992.
7. Tenkink, E. *Determinanten van rijsnelheid.* Rapport IZF 1988 C-3. Instituut voor Zintuigfysiologie TNO, Soesterberg, the Netherlands, 1988.
8. Tenkink, E. *De invloed van wegbreedte en obstakeldreiging op snelheids- en koersgedrag.* Rapport IZF 1989 C-4. Instituut voor Zintuigfysiologie TNO, Soesterberg, the Netherlands, 1989.
9. Tenkink, E., and A. R. A. van der Horst. *Effecten van wegbreedte en boogkenmerken op de rijsnelheid.* Rapport IZF 1991 C-26, Instituut voor Zintuigfysiologie TNO, Soesterberg, the Netherlands, 1991.
10. Riemersma, J. B. J., W. Hoekstra, A. R. A. van der Horst, G. M. M. Alink, and N. Otten. The Validity of a Driving Simulator in Evaluating Speed Reducing Measures. *Traffic Engineering and Control*, Vol. 31, No. 7, 1990, pp. 416–420.
11. Tenkink, E. *Effecten van wegbreedte en een additionele taak op rijsnelheid en koersgedrag.* Rapport IZF 1990 C-27. Instituut voor Zintuigfysiologie TNO, Soesterberg, the Netherlands, 1990.
12. Horst, A. R. A. van der, W. H. Janssen, and J. E. Korteling. Measuring Effects of Variable Message Signing on Route-Choice and Driving Behaviour. *Proc., SHRP Conference*, Gothenburg, Sweden, Sept. 18–20, 1991. VTI Rapport 372A, Part 1. Swedish Road and Traffic Research Institute, Linköping, Sweden, 1991, pp. 75–84.
13. Horst, A. R. A. van der, and W. Hoekstra. *Effecten van snelheidsbeperkende maatregelen op 80 km-wegen Drenthe op het rijgedrag: Een Simulatorstudie.* Rapport IZF 1992 C-30, Instituut voor Zintuigfysiologie TNO, Soesterberg, the Netherlands, 1992.
14. Oei Hway-liem, and W. H. M. van de Pol. *Rijsnelheden op 80 km/uur wegen in Nederland II, Verslag van snelheidsmetingen in twaalf geografische gespreide gebieden in Nederland.* Rapport R-91-24, Stichting Wetenschappelijk Onderzoek Verkeersveiligheid SWOV, Leidschendam, 1991.
15. Bakker, P., and A. R. A. van der Horst. *Het rijgedrag van automobilisten onder invloed van een kantstrookversmalling.* Rapport IZF 1987 C-18, Instituut voor Zintuigfysiologie TNO, Soesterberg, the Netherlands, 1987.
16. Armour, M. *Effect of Road Cross Section on Vehicle Lateral Placement.* Vol. 15, No. 1, Australian Road Research Board, 1985, pp. 30–40.

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