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The Effects of Road Design on Speed Behaviour: A Literature Review

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Partners:
FACTUM Chaloupka, Praschl & Risser OHG (FACTUM, Austria)
University of Leeds - Institute for Transport Studies (ITS, U.K.)
KTI Institute for Transport Sciences Ltd (KTI, Hungary)
Lund University - Dept. of Traffic Planning and Engineering (LU, Sweden)
TNO Human Factors Research Institute (TNO, the Netherlands)
Transport Research Laboratory (TRL, U.K.)
University College London - Centre for Transport Studies (UCL, U.K.)

Associate partners:
INTRA S.L. (Spain)
TRANSPOR (Portugal)
SWOV Institute for Road Safety Research (the Netherlands)
Swedish Road & Transport Research Institute (VTI, Sweden)

Author:
Marieke Martens, TNO Human Factors Research Institute, The Netherlands,
Samantha Comte, University of Leeds, U.K.
Nico Kaptein, TNO Human Factors Research Institute, The Netherlands

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Summary

Controlling driving speed is considered to be an effective way of improving driving safety; driving speed plays an important role in accident occurrence, since higher speeds lead to increased accident probability and severity.

This literature review contains an overview of the efficacy of various speed reducing measures. Measures that affect driving speed directly are discussed, but special attention is paid to factors that affect driving speed indirectly, i.e. by influencing the willingness to show the appropriate speed behaviour. Advantages and disadvantages of various measures are discussed.

Currently, the largest reductions in driving speed are realised with speed reducing measures that physically restrict driving at high speeds. Since this only forces road users to reduce speed, but does not let them choose this voluntarily, a more optimal solution is to design roads that are “self-explaining”. By designing a road that provides a speed image, that is in accordance with the actual speed limit, drivers will choose the appropriate driving speed more or less automatically. Currently, subjective road categories do not seem to correspond with the official road categories. Yet, no research has addressed the exact relationship between subjective road classification and actual driving behaviour. Within the framework of MASTER, this relationship will be investigated by means of driving simulator experiments.

CONTENTS

1 INTRODUCTION

The majority of accidents at high speeds results in severe or fatal injuries (NHTSA, 1991). The introduction of a higher interstate speed limit in the United States resulted in an increase in fatality and injury rate (Wagenaar, Streff & Schultz, 1990). Sabey (1983) and Sabey and Taylor (1980) suggested that high driving speed is a contributory factor in about 23% of the accidents in the UK. There is a clear relationship between the speed level and the number of accidents (e.g. Varhelyi, 1996). The seriousness of the outcome of an accident increases with increasing speed level, since high speeds increase the exposure to dangerous situations, and impose restrictions on the time available to respond properly in unexpected situations. When a fast moving vehicle is involved in an accident the consequences are worse than they would be at lower speeds. Several studies (e.g. Salusjärvi, 1981; Nilsson, 1981, 1988; Johnson, Klein, Levy & Maxwell, 1981; Christensen, 1981) show that reductions in average driving speed of 2 to 5 km/h can result in a reduction in injury and fatal accidents of up to 30%.

Besides actual driving speed, the distribution of driving speed plays an important role in accident risk (e.g. Hale, 1990; Finch, Kompfner, Lockwood & Maycock, 1994; O’Cinnéide & Murphey, 1994). Studies have shown that there is an important statistical relationship between speed variance and accident rate (Pisarski, 1986; Ministry of Transport and Communications, 1974). On motorways, accident risk increases as vehicle speed deviates from the average speed. Garber and Gadiraju (1989) state that the variance in speed depends on the level of the actual driving speed. This is affirmed by the fact that the amount of fluctuations in speed is much higher on motorways than on rural roads, although this can partly be explained by the difference in driving speed between various sorts of vehicles on motorways. If there are larger differences in speed between vehicles in a traffic stream, slower moving traffic may form an obstacle for faster traffic.

It is not always the case that drivers violate speed limits on purpose. There is a tendency to underestimate one’s own driving speed due to negative speed adaptation, if one has driven at a continuous high speed for a certain period of time (Schmidt & Tiffin, 1969; Irving, 1973; Denton, 1976). Besides the safety aspects of high speeds, high speeds result in increased air and noise pollution. However, sometimes low speeds can have negative effects too. Low speeds may lead to reduced arousal and attention, may restrict traffic flow and road capacity, and may cause local congestion if traffic volumes are moderate to heavy. This congestion can increase the potential hazard for rear-end accidents. Therefore, it may be useful to decrease speed only to some extent. The most optimal solution would be to reduce speeds up to the level that permits good anticipation and allows high traffic flow, but does not result in the disadvantages of really low speeds. Besides actual level of driving speed, speed variance should be minimal.

Placing a sign that shows the speed limit does not automatically imply that drivers also choose the indicated speed. Speed violations are the most common traffic violations. Brogt (1978) states that this is the consequence of the fact that the design speed of a particular road is not in accordance with the posted speed limit. This means that the indicated speed limit is not in accordance with the speed limit the road was originally designed for.

Richards and Dudek (1986) refer to posting a reduced speed limit on a static sign as passive speed control. Passive control alone is generally only sufficient at sites where the hazards are obvious, and drivers understand and accept the speed limitation. Donald (1992) carried out a study examining the relative effectiveness of different types of speed signs in attempting to slow down traffic from 100 km/h to 60 km/h at the approaches to rural cities and towns. It turned out that neither a 80 km/h sign erected 300 m in advance of the 60 km/h sign at the edge of the town, nor a “60 ahead” sign, 300 m in advance nor different sized 60 km/h signs without additional signing were very effective in slowing down traffic to 60 km/h. However, the use of the advance warning sign or the 80 km/h sign slowed traffic by a significantly greater amount than the use of a 60 km/h sign only. Yagar (1984) showed that speed limit signs may have some effect, for instance in Ontario, where driving speed on rural 2-lane highways was partly affected by the presence of signs.

Oei and Polak (1992) showed that a feedback message such as “You are driving too fast” led to a speed reduction of 6 km/h on rural roads, although the radar posts might also have had an effect. The percentage of drivers exceeding the speed limit decreased from 38% to 11%. Active signalling, by means of a dynamic sign, has more effect than passive control, since drivers may also interpret the signal as an indication for upcoming danger. However, the fear of receiving a speed ticket probably also plays a large role. A Variable Message Sign, indicating a fog warning and a lowered speed limit decreased driving speed by about 10% and the number of accidents by about 20% (Balz & Zhu, 1994). This speed reducing effect was confirmed in a driving simulator experiment which found speed reductions of about 8−10 km/h (Hogema, van der Horst and Bakker,1994). A rather efficient kind of active feedback was provided by Van Houten and Nau (1983) and by Maroney and Dewar (1987), whereby road users received feedback about the percentage of drivers who were not speeding. A 40% decrease in driving speed was found and the number of drivers exceeding the speed limit reduced by 50%. Even after several weeks, and after the removal of the sign, there was still a significant speed reduction.

The effectiveness of variable speed limit signs around school zones was investigated by Pak-Poy and Kneebone (1988). Sign posts that displayed the combination of the standard speed limit sign, a school zone sign and a sign outlining the hours of operation lead to reductions in the mean speed from approximately 60 km/h to 46 km/h, but general compliance with the 40 km/h speed limits was not attained.

When discussing the effect of speed limit signs on driving speed, it should be kept in mind that it is rather difficult to measure the exact influence of a speed limit on driving speed, since the speed limit will be related to some extent to the infrastructure of the road (Marconi, 1977).

Law enforcement is employed in an attempt to increase compliance to speed limits. If road users notice or suspect their driving speed is being monitored by radar or police control, they will usually decrease their driving speed due to the fear of citation. Galizio, Jackson and Steele (1979) found that out of a speed limit, a radar-enforced sign and a marked police car, only the police car had a significant effect on driving speed. They concluded that the threat of punishment rather than safety or efficiency was the underlying cause of this. Barnes (1984) determined that the response of motorists to a marked police car was to start reducing their speed more than 2 km before reaching the actual enforcement site. In the vicinity of the enforcement site, speeds were appropriate for the speed limit, but motorists accelerated quickly after the site and returned to their pre-enforcement speed within a distance of 4 to 6 km. The effect that speed reductions are only found some distance before to some distance past the enforcement site, is called the distance halo effect and is usually measured in kilometres upstream and downstream. Armour (1984) studied the effect of police presence in the form of a marked police car on urban streets. Speed surveys were carried out to determine the proportion of drivers exceeding the speed limit before, during and after the enforcement period. The presence of a police car brought about a reduction in the proportion of drivers exceeding the speed limit by approximately 70% at the test site, but the effects did not last very long past the site. However these speed reductions persisted for up to two days after the removal of the enforcement. The effect that speed reductions are found from encountering the enforcement activities to some time after removal of the enforcement site is called the time halo effect and is commonly measured in days. Drivers tend to slow down on subsequent occasions of passing the enforcement site, since they expect to encounter enforcement. Nilsson and Sjorgen (1981) investigated the effect of a number of different kinds of enforcement, involving marked and unmarked police cars, radar and helicopters. Following six days of enforcement, the duration of the time halo for both the radar and the marked police car was of the order of 10 days, whereas for helicopter surveillance, it was in the order of 17 days. Unmarked police cars had no time halo effect. Hauer, Ahlin and Bowser (1982) concluded that repeated exposure to enforcement had no impact on the distance halo effect, but did produce a dose dependent time halo effect. While the residual speed reducing effects of one day of enforcement endured for up to three days, five days of enforcement resulted in a time halo of at least six days. A report by Vaa, Christensen and Ragnøy (1995) describes experiments on four stretches of road on which the police increased the level of speed enforcement using stationary methods. The duration of the speed enforcement was 5.4, 4.8, 3 and 1.4 hours per day each day for six weeks. Speed was measured before, during and after the period of enforcement increase on each of the experiment stretches of road and on reference stretches of road. On the stretches of road applying 5.4 and 3 hours of enforcement per day, the effects were the most profound. Both the average speed and the number of speed violations were reduced and time halo effects of a maximum of 10 weeks were observed.

The problem with law enforcement is that the realisation of an overall high chance of apprehension is extremely expensive (Armour, 1984). Besides this, enforcement will only work if drivers actually know that they are speeding, notice or suspect their driving speed is being monitored, and if the delay between the actual speed violation and the ticket is kept to a minimum. Raising the fine does not seem to have any effect on driving speed. Bjornskau and Elvik (1992) conclude that, in general, enforcement will not have lasting effects and that stricter penalties will not affect driver behaviour. Enforcement should only be used to punish drivers that deliberately violate the speed limit. However, the most important problem with law enforcement is that even though it may decrease driving speed, the driver's attitude toward speeding is not changed. Enforcement can best be seen as an external variable that influences behaviour without affecting the intention to display the appropriate speed behaviour (Rothengatter, 1982).

An alternative way to control driving speed is to influence speed indirectly via the driver's perception of the appropriate speed for a particular road. Under some conditions, drivers may not be aware they are speeding. By influencing the driver's perception of the traffic situation, the driver may assume a lower speed is more appropriate leading to higher acceptability of a lower speed. As speed perception depends on cues in the visual environment, the road environment could be changed to distort drivers' perception of speed and thus encourage lower speeds. It is important that the road triggers the right expectations about which driving behaviour is appropriate and thus allow drivers to perform that driving behaviour more or less automatically. This paper concentrates on the effect of such adaptations in road design on speed behaviour. It contains a literature review of speed reducing measures as part of the MASTER- project PL95-66 (Managing Speeds of Traffic on European Roads). The purpose of the project is to gain information for national and EU speed management strategies and policies and standards for speed control equipment. This literature review is part of WP 2.3, Road Design and Speed Behaviour and aims to give an overview of the effects of road design on speed behaviour.

2 ADAPTATIONS IN ROAD DESIGN

With a proper lay-out of a road, the road environment can indicate to road users that high speeds are not appropriate and can even suggest they are impossible. It seems logical that the driving speed on wide concrete rural roads with dual carriageways will be different than the speed chosen on small one-lane roads in a residential area. On a properly designed road, road users do not have the idea that they are forced to drive at a lower speed, but that they choose this lower speed voluntarily. Therefore, the possibility for long term effects is increased and dangerous side effects such as those linked with speed humps are not present. Fildes and Jarvis (1994) emphasise the importance of these changes in road design, which are a mixture of sensory and cognitive aspects (Fildes & Jarvis, 1994). By adapting the road design, roads may become “self-explaining” in that their lay-out explains what driving behaviour is expected. A traffic environment which provokes the right expectations should therefore reduce potential errors.

This concept of Self-Explaining roads (SER) has been discussed by Theeuwes and Godthelp (1992), Theeuwes (1994), and Kaptein and Theeuwes (1996). The traffic environment should provoke the right expectations concerning the presence and behaviour of other road users as well as the demands with regard to their own behaviour. In order to reach this goal, clearly distinct road categories must be used, each requiring their own specific driving behaviour. Current road design does not provide road users with a clear picture of which road belongs to what category. Experiments with road categorisation based on photos and videos have shown that official road categories do not correspond with the subjective road categories that road users have (Riemersma, 1988a; Theeuwes, 1994; Kaptein & Theeuwes, 1996). This may lead to driving behaviour that is not appropriate for the traffic situation. Only motorways form a clearly distinct road category, where drivers have a good idea of what to expect and what is expected of their own driving behaviour. In order to achieve this for the complete road network, the idea of SER can also be used for non-motorways to provoke the right expectations with regard to speed behaviour. Of course, attention must also be paid to transitions from one road category to another.

Sequentially, some road design factors that have an effect on driving speed will be discussed.

2.1 TRAFFIC CALMING MEASURES

Traffic calming measures, like the alteration of the vertical profile of the road (speed humps and raised junctions) or the creation of horizontal deflections such as chicanes can be used to discourage speeding on roads within built-up areas.

2.1.1 Speed Humps

A speed hump is a local elevation of the road surface of limited length − up to 3.5 m − and normally about 0.15 m high and may decrease the original driving speed up to a resulting speed of 10 km/h. The amount of speed reduction achieved using speed humps can be influenced by adjusting the height and length of the undulation. The problem with short humps (up to 2 metres) is that they hardly cause any discomfort at high driving speeds. With an average length (2 to 3 m), a too low speed causes high discomfort (De Wit & Slop, 1984). Stephens (1986) reviewed a number of empirical studies on the effectiveness of speed humps in Australia, the USA and England. The speed reductions observed at the various sites varied with the pre-installation speed, and the largest reductions of about 40 km/h were observed at those sites where the pre-installation speed was highest (about 70 km/h). Webster and Layfield (1993) investigated the speed reducing effect of 0.075 m high speed humps on several sites in the UK. They concluded that these humps can be used to reduce speeds to below 32 km/h. Watts (1973) found that a 0.10 m high, 3.7 m long circular shaped hump was the most successful in decreasing driving speed to 30 km/h. Engel and Thomsen (1992) attributed speed humps a speed reducing effect of one km/h reduction in driving speed for every cm increase in height of the hump.

Although speed humps are rather effective in reducing driving speed in urban areas, there are some problems with using speed humps. They are not too popular with road users, especially not with bus drivers and passengers and they also lead to more variance and abrupt changes in driving speed. A lot of complaints about speed humps are also received from residents, fire departments, police and ambulance services. Emergency services may have trouble passing them in case of an emergency; there may be problems with large vehicles and vehicles that carry heavy load as they cause lateral displacements on the road, and they increase fuel consumption (Gorman, Moussavi & McCoy, 1986; Stephens, 1986). Speed humps affect large vehicles in a different way, normally more than normal cars. Therefore, the use of undulations on roads that carry a certain amount of large vehicles should be discouraged. Buses form a special problem since they often travel on roads in residential areas. Since residential areas usually do not meet the criterion of a large amount of large vehicles, speed humps are implemented. In these areas, authorities should attempt to avoid undulations or design humps for cars in a way that buses can pass without being affected.

Additional problems include increased noise level, the possibility of drivers avoiding them by driving on the grass, and damage to cars. Speed humps are only to be implemented on urban roads, and they limit the parking space in residential areas. It is also possible that the installation of traffic calming measures on isolated roads causes local diversions onto other roads and thus creates accident migration. Another common problem with speed humps is that people tend to make up the loss of time by driving with extra high speed on adjacent road parts that allow (but not permit) high speeds (Tenkink, 1988). So speed humps can only be used on urban areas, they tend to be only locally effective and can even increase driving speed on adjacent road stretches, thereby decreasing safety on these road parts. Petterson (1981) showed that, although driving speeds were reduced when speed humps were installed, the speed profile was very uneven, because drivers decelerate very strongly before the speed hump and increase their speed immediately after the hump. Sometimes it is even suggested that speed humps may lead to an increased loss of control of two-wheeled vehicles, which clearly decreases safety (Mak, 1986). The most common complaint about speed humps is that drivers receive punishment even if they drive at a relatively low speed. The best way to implement speed reducing measures would be to punish only road users that drive too fast (Herrstedt, 1995; Van der Horst & Hoekstra, 1992). If speed humps are used, it is important to warn road users and give an indication for the appropriate driving speed. To avoid any accidents with motorists that do not notice the traffic hump, they must be made clearly visible.

2.1.2 Horizontal Deflection

Von Mörner (1984) demonstrated that the amount of road over which the driver has unobstructed vision is important in speed judgements. Thus road narrowings that have very little height above the road surface hardly obstruct vision on road width. The effectiveness of short road narrowings can be enhanced by the addition of vertical elements such as trees and lamp posts, the combination of which is often called a gateway treatment. Von Mörner also suggests that the optimal configuration should create 45 degree changes in direction of the carriageway, approximately every 50 m with an offset of the full width of the carriageway. The full width offset blocks the motorists view of the road farther away, thereby dividing the road into small sections. Some narrowings rely on vehicles passing in the opposite direction in order to result in speed reductions. However, these narrowings might result in a reduction in traffic safety, as a consequence of conflicts between opposing traffic. A further problem with road narrowings, especially with high traffic intensity, is that there is no gradual reduction in driving speed and large and rather abrupt changes can occur.

2.1.3 Roundabouts

Roundabouts are effective in breaking up long stretches of road that otherwise might encourage speeding. Herrstedt (1992) suggests that roundabouts can be an effective speed management tool but their effectiveness is mediated by the extent to which drivers are forced into an actual roundabout manoeuvre. A large roundabout, used to mark the entrance to a small town was successful at reducing traffic speeds, whilst a mini-roundabout did not reduce speeds to an appropriate level. Mini-roundabouts have been introduced in increasing numbers in recent years as replacements for priority junctions, often to improve operating efficiency by altering the balance of priority in favour of hitherto dominated streams. Mini-roundabouts are also frequently installed at new junctions.

Lynam (1987), Schull and Lange (1990) and Davies (1988) found that roundabouts were successful at reducing vehicle speeds and breaking up the perceived straightness of the road. Several studies have found that mini-roundabouts at intersections do decrease the number of accidents considerably (NVF, 1984; Hyden et al., 1995; Seim, 1991, Simon, 1991; Van Minnen, 1992). This may be the result of the warning character of the mini-roundabout, that increases the attention level.

Varhelyi (1993a) describes a traffic safety experiment with mini-roundabouts as speed reducing measures in a Swedish town. The effects of the measures were evaluated in different studies. Most of the results were positive. The level of safety increased, the interplay between road users improved, and traffic noise decreased. The negative effects, i.e. time losses for car drivers and an increase in emissions on the main roads, were minimal. Varhelyi (1993b) also describes intersections which were converted to mini-roundabouts. Apart from safety aspects, their effects on speed, time, petrol consumption and emissions were studied with reference to speeds before and after construction of mini roundabouts. Speeds were considerably reduced, not only at intersections but also in links between them. The average speed reduction was from 48 km/h to 35 km/h. The speed reduction at T-junctions was less than at 4-way intersections. The speed reduction depended on the lateral displacement, required from the road user. The time taken to travel through the mini-roundabout rose for cars on major roads and dropped for those on minor roads. If environmental effects are being considered, CO-emission for an intersection after installation of a roundabout increased by 6%, and petrol consumption by 3%. For the entire influence area of mini-roundabout system (8 km major and 4 km minor roads), CO emissions rose by 2%, and petrol consumption by 0.4%.

Roundabouts are a relatively safe kind of junction, since safety at intersections increases by locally reducing speeds. However, without wanting to introduce many decelerations and accelerations, it seems less plausible to install roundabouts on straight road sections outside the built-up area as a means to reduce mean driving speed.

2.1.4 Village Gateway Schemes

During 1992, gateways were installed on the approaches to several villages in England (Wheeler, Taylor and Barker, 1994). Speeds of freely moving vehicles were recorded before and after installation. At a number of sites monitoring was carried out twice after implementation of the measures to assess their long-term effects. It was recommended that speed reductions in villages will only be achieved if stringent measures are used. These measures should be aimed at physically reducing speed and should be applied at regular intervals along a route to maintain reductions. The study made clear that the design and siting of measures need careful consideration. It appears that the visual impact of the gateway is important, where contrasting red/white road surfaces and the ‘30’ roundel have been particularly effective. Gateways should be sited away from features that already constrain speed, such as bends and summits. It appears that gateways are more suitable for wider roads than on narrower roads where there is less opportunity to provide horizontal deflection by, for example, narrowing and central islands. Advance warning signs of speed reducing measures may make the measures more effective by influencing drivers who do not know what they are about to encounter. Detailed design should be considered from all angles, in particular if measures are close to a junction, possible changes in sight-lines need to be checked. This suggests the need for a 'safety audit' type of approach.

Riemersma, Van der Horst, Hoekstra, Allink and Otten (1990) also studied the speed reducing effect of village gateways. They used different measures such as yellow poles to give the impression the road gets narrower, a 50 km/h sign, different coloured pavement and a central island 140 m before the gateway. These measures resulted in a decrease in mean driving speed from 77 km/h to 66 km/h, although the driving speed was still above the indicated 50 km/h. This also held true for the observation of Wheeler et al. (1994) who combined a number of speed reducing measures such as gateways, surface treatments and road narrowings in an attempt to reduce the speed drivers choose while passing through villages. Although driving speed was reduced, the mean speed level was still over the speed limit.

2.2 ROAD WIDTH

Before discussing the effect of road width on speed, a distinction must be made between different aspects of road width. A distinction will be made between lane width, width of pavement, lateral clearance and effective road width.

2.2.1 Lane Width

Lane width plays a role in driving speed, since smaller lanes lead to more influence of other traffic (meeting traffic or overtaking traffic) and of obstacles along the side of the road. With smaller lanes, more effort must be put into lane keeping and steering behaviour. As a consequence, driving speed usually decreases with lane width.

With decreased lane width, drivers show improved lane keeping, more accurate steering behaviour and a reduction in driving speed usually results. Yagar and Van Aerde (1983) found a reduction in speed of 5.7 km/h for every metre of reduction in lane width beyond 4 m. A positive relationship between vehicle speed and lane width was also found by Vey and Ferreri (1968), who found higher speed for 3.4 m wide lanes than for 3.0 m wide lanes measured on two comparable bridges in Philadelphia. It must be kept in mind that this only works to some extent. Decreasing lane width beyond a certain point (close to the width of the car) makes driving practically impossible. Furthermore accidents may occur if road users do not adapt their speed to this decreased road width in order maintain a safe level of driving performance (Jacobs, 1976; DeLuca, 1985; Lamm, Choueiri & Mailander, 1989).

The effect on driving speed also depends on the kind of measure that is taken. In this respect, a study by Van der Horst (1983) is of interest. Van der Horst found an increase in driving speed of 7.5 km/h with a reduction in lane width from 4.6 m to 3.6 m. In this study, lane width was decreased by installing a central area between the two driving lanes, which improved visual guidance, provided by the presence of road markings on both sides of the roads in the new situation, and the central vehicle-free area between the two driving lanes. Reducing lane width is an effective measure to decrease speed, but it will only be acceptable as long as it does not result in an increase in accident rate

2.2.2 Width of Pavement

Both driving lanes and extra pavement strips on the left and right side of the road, for instance an emergency lane, contribute to the total amount of pavement width. This additional space provides some extra driving space in case of necessary lateral displacements or lane recovery. This way drivers' uncertainty is decreased, something which usually leads to higher speeds. The pavement strips can be of the same quality as the road surface, but also of an inferior material, like bricks.

De Boer (1986) investigated the cues that drivers use for determining the speed limit. It seems that road users use pavement width as the major cue for determining the speed limit in residential areas. Yagar and Van Aerde (1983) found a small increase in driving speed on 2-lane rural roads if an emergency lane was added. This finding was affirmed by Van Smaalen (1987) and Kolsrud (1985), who found a positive correlation between pavement width and speed on rural roads, where wide pavement increased driving speed, even though the speed limit was kept the same. The mean speed with a pavement width of approximately 6 m is about 80 km/h and with a width of 8 m, the mean speed increases to about 90 to 100 km/h (Van der Hoeven, 1987). With decreased pavement width, the same kind of problems as indicated in section 2.1.1 may arise if road users do not sufficiently compensate for this reduction in available driving space. However, extra pavement width, such as extra available space next to the driving lanes does not always have to affect driving speed. Bakker and van der Horst (1987) found that on a two-lane road with driving lanes of 2.85 m wide, a decrease in the width of sealed shoulders from 1.20 m to 0.30 m only decreased speed in case of opposing traffic (about 4 km/h).

It is very difficult to measure the effect of pavement width in itself, independently of other road design factors. This can probably explain the fact that the relationship between width of pavement and driving speed was established in some studies (e.g. Van de Kerkhof & Berénos, 1989; Van Smaalen, 1987), whereas in other cases no effects could be found (e.g. Brenac, 1989). Fildes, Fletcher and Corrigan (1987) also indicate that a reduced road width and a reduced number of lanes normally leads to a reduction in speed on urban and rural roads, although this also correlates with different kinds of roads and the speed limit. Von Mörner (1984) demonstrated that in the relationship between carriageway width and speed, it is the perceived width that is important. Smith and Appleyard (1981) also report a direct relationship between drivers' speed and apparent width of carriageway, which encompasses the influence of the immediate surrounding environment on the actual road surface (a perceptual interpretation of a geometric feature).

2.2.3 Lateral Clearance

Lateral clearance indicates the space between obstacles to the left and the right side of the road or the space that is visually available between obstacles on either side of the side walk. In this case, obstacles can be front gardens, overgrowth, lamp posts, ditches beside the road, parked cars etc. (Van de Kerkhof, 1987). Although lateral clearance covers more than width of pavement alone, under some conditions, for instance in case of a barrier just along the side of the road, pavement width and lateral clearance refer to the same space.

Reducing lateral clearance to reduce driving speed works to some extent. A reduction of lateral clearance from 30 m to 15 m decreases speed by only 3%. However, when lateral clearance is decreased to 7.5 m, a speed reduction of 16% is found (Van der Heijden, 1978). This indicates that reducing lateral clearance only results in larger speed reductions beyond a certain point. Its effect also depends on the kind of shoulder (soft, hard) and the amount of danger associated with leaving the road (for instance hitting a tree). Therefore, there is a relationship between the distance of the car to obstacles in the shoulder and driving speed. With obstacles directly along the side of the road (reduced lateral clearance), driving speed reduces about 13% compared to obstacles placed one metre away from the edge of the road (Knoflacher & Gatterer, 1981). This may also have something to do with the obstacles taking away some of the sight distance (there is further discussion on the effect of obstacles on driving speed in 2.2.7).

An example of lateral clearance affecting driving speed is the Krusemanlaan in the Netherlands. This urban street encouraged car users to drive faster than the permitted 50 km/h by its wide view and wide road sides (Directie Verkeersveiligheid, 1987). Altogether, 81% of the car drivers drove faster than was actually permitted. By reducing the spacious image, a much smaller group ignored the speed limit (58%). Yet, the actual speed reduction was only limited.

2.2.4 Effective Road Width

Another measure for road width, that has a slightly different perspective than the other measures is the effective width of the road. This indicates the amount of pavement that is actually available for road users to drive on. Under some conditions, the effective road width may indicate the same thing as width of pavement, but for instance in the case of parked cars on the road, the effective road width is much smaller than the actual width of pavement.

A literature study by Van der Hoeven (1987) was aimed at investigating speed behaviour on 80 km/h rural roads. In this study special attention was paid to rural roads. Rural roads are linked to high accident rates, caused by the presence of traffic travelling in the other direction – at relatively high speeds –, which reduces the effective road width. The reduction of effective road width by parked cars is even of greater importance than a reduction of actual pavement width. The reduction in speed by the presence of parked cars can mainly be explained by the number of parked cars on the right side of the road. Smith and Appleyard (1981) also showed that vehicle speed was positively correlated with perceived road width, which was strongly influenced by the presence of parked vehicles. The effect of effective road width on driving speed is confirmed in several studies, with smaller effective road widths leading to lower speeds (Van de Kerkhof & Berénos, 1989; Tenkink, 1990; Van der Horst & Hoekstra, 1992).

2.3 ROAD MARKINGS

Road markings are line treatments on the road surface, that provide guidance and regulatory warning information to the driver. For lane keeping and anticipation of the course of the road, road markings are extremely important. A literature review by the OECD (1990) suggests that the presence of road markings on two-lane rural roads produces a safety benefit. However, this finding is not in accordance with Elvik, Borger and Vaa (1996). In a summary of studies from different countries, they did not find reductions in number of accidents as a consequence of the presence of centre line and edge line markings.

Side markings and centre line markings can serve as a cue to show the correct path to follow and transverse road markings can serve as a possible warning. Road markings reduce the amount of crashes, especially the amount of crashes caused by drunk driving (Noordzij, 1996). Road markings are of great importance for driving safety, but their presence (e.g. Van der Horst, 1983), as well as the presence of reflector posts (Kallberg, 1993), can also cause an increase in speed, especially at night since they reduce driver's uncertainty by allowing anticipation and providing visual guidance. In a study by Van der Horst (1983), improved visual guidance, provided by the presence of road markings on both sides of the road and a central vehicle-free area between two driving lanes caused an increase in driving speed, even though lane width was reduced from 4.6 m to 3.6 m.

Besides the most common type of road markings, centre line and edge line markings, placed along the road axis, other types of pavement markings can be found. Transverse marking patterns – as well as decreased spacing between the centre line markings – can decrease speed, since this leads to the illusion one is driving faster than one actually does or that one is even accelerating. Transverse road markings are especially suitable for reducing speed on the approach to a dangerous site, for instance in front of a dangerous crossing, a roundabout or a bend. Fildes, Fletcher & Corrigan (1987) found that the use of herringbone road markings along the side of the road that increase in frequency while approaching a dangerous location, led to a reduction in mean driving speed. The same finding is reported in other studies, that putting transverse markings on the road surface at the entrance to a curve, leads to a reduction in approach speed (Denton, 1971, 1973; Rockwell & Hungerford, 1979; Agent, 1980). Besides reductions in mean driving speed, reductions in speed variance are reported (Denton, 1973). Since the markings increase in number, this probably alerts the driver and leads to a decrease in speed. There is some uncertainty about the durability of the speed reductions. Havell (1983) suggests that effectiveness of such measures can be maintained for months whilst others suggest the benefits fade in a matter of days or weeks (e.g. Maroney & Dewar, 1987). A decrease in effectiveness of transverse road markings over time was also reported by Maroney and Dewar (1987). They investigated the effect of reflective white lines, painted transversely on a road exit. It turned out to be an effective way to reduce extreme speeding by 25%, but after 3 weeks this effect started to decrease.

Burney (1977) looked at the effect of yellow road marking patterns on speed. She chose a pattern of 90 transverse yellow road markings from 440 m to 35 m before entering a roundabout. The pattern reduced approach speed and some drivers even started decelerating before they actually hit the pattern. Apparently the pattern worked as a kind of visual warning for a dangerous situation. Jarvis (1989) also discusses the effects of yellow road markings on speed and he even found a speed reduction after more than 12 months. His opinion was that the reduction could be attributed to the markings serving as a large warning signal that cannot be ignored. Uber (1992) compared the effect of white and yellow markings on driving speed and found a larger reduction in driving speed for white road markings.

Rockwell, Malecki and Shinar (1974) looked at the effect of safety measures on driving behaviour in bends outside a built-up area. Transverse lines were placed about 375 m before the bend with decreased spacing between the lines while approaching the bend, emphasising the inner side of the bend by widening the inner edge marking, and using the Wundt-illusion (a herringbone structure from about 175 m before the bend that stimulates the illusion of a road decreasing in width just before the bend). Transverse lines only effectively decreased speed for freight vehicles, since drivers of these vehicles look at the patterns from a higher perspective, which enlarges the effect. At night, transverse lines have more effect than during the day, probably since nighttime driving limits anticipation and visibility itself. Emphasising the inner side of the bend reduced speed during the approach and just before the actual bend. The Wundt-illusion decreased speed just after entry to the bend. However, after 30 days, the reductions in driving speed due to these three measures had completely disappeared. Witt and Hoyos (1976) reported that in their simulator experiment, a varying pitch broken edge line in the approach to a road curve resulted in drivers adopting a more suitable speed profile while negotiating a curve. Rockwell, Malecki and Shinar (1974) also report that novel road markings can influence perceived speed and roadway width on curves. However, Hungerford and Rockwell (1980) note that these influences may be site specific and might not necessarily endure in time.

Lum (1984) found no effect of narrow longitudinal road markings on either mean speed or speed distribution on straight sections of road at residential sites. Cottrell, Deacon and Pendleton (1985) failed to show any difference in speed on straight roads for wide edge lines and it would appear that the major benefit for edge lining on straight sections of two-way rural roads is for maintaining a safe position within the lane itself (Triggs & Wisdom, 1979; Triggs, 1986; Cottrell, Deacon & Pendleton, 1985). This led to the idea that road markings are effective speed reducing measures if they reduce effective road width, although under some conditions, the visual guidance provided by road markings can neutralise the effect (e.g. Van der Horst, 1983). Fildes, Leening and Corrigan (1989) used a white separation line painted on the pavement in longitudinal direction between the moving and the parked vehicles, which reduced effective road width from 5 to 3.7 m. Altogether this resulted in a speed reduction of 5%. This finding again indicates that a lot of countermeasures are interconnected. Changing one road characteristic may very well influence other road characteristics, which makes it hard to estimate the exact influence of every measure in itself.

2.4 BUILDINGS AND OVERGROWTH

In a study by Van de Kerkhof (1987), driving speed on roads inside the built-up area was found to be affected by the presence of buildings along the side of the road. In his study, personal characteristics, weather influences or police control influences were not investigated, since they will always vary and cannot be influenced explicitly. Buildings that are positioned next to the investigated road surface and are visible for the driver, reduce driving speed. Smith and Appleyard (1981) reported that the distance of housing to the road was positively correlated with urban car speeds.

There is also an effect on driving speed of the number of visible entries and exits on the right side of the road, and the amount of overgrowth (Van de Kerkhof, 1987). The more entries and exits to the right side of the road, the lower the mean driving speed. The amount of overgrowth may influence speed in two ways. First of all, it can serve as guidance, thereby increasing driving speed. Second, if there are groups of bushes or trees rather than a continuous wall of overgrowth, they do not serve as guidance, but rather function as accents. This may increase the attention level of the driver, increases the amount of flow in the peripheral vision (See paragraph 2.5) and speed will (be assumed to) decrease.

Slangen (1983) reported lower speeds on roads with trees or houses close to the road (speed reduction of 12-14%). Van de Kerkhof and Berénos (1989) found the following environmental features to have an effect on driving speed in urban areas: the amount of houses (more houses, lower speeds) and amount of cars parked on the right and left side and the amount parked on the right side only (more parked cars lead to reduced speeds due to a reduction in the effective road width).

Rural roads with no prominent features result in an underestimation of one’s own driving speed, whereas similar tree-lined roads do not (Shinar, McDowell & Rockwell, 1974). Triggs (1986) suggested that this effect is the result of either increased peripheral stimulation or motion parallax effects (see also 2.5). Fildes et al. (1987) also reported that speed perception effects were dependent on the road side development. In rural environments, roads without trees were perceived as safer and travelling speeds were underestimated much more than on heavily tree-lined roads.

Marconi (1977) indicated that there may also be some disadvantages attached to buildings and planting close to roads. Buildings and planting may cause distraction and limit visibility, possibly leading to problems since anticipation on road exits or crossing pedestrians can be difficult.

2.5 ROUGHNESS OF ROAD SURFACE

Roughness of road surface is a measure of the amount and type of deviations from a smooth road surface. There exists longitudinal roughness (e.g. bumps in asphaltic concrete in front of traffic lights), transverse roughness (e.g. tracks that can cause aquaplaning), road surface irregularities (e.g. holes in the road surface) and then there is roughness caused by road material (e.g. a brick road). Irregular road surfaces result in a certain amount of noise and vibration, thereby decreasing driver comfort. The effect on driving speed is not the result of the roughness of the road surface per se, but rather an effect of a reduction in driver comfort. A road surface can be described in terms of material and structure, micro-roughness and colour (Wildevanck, 1987). A subtle measure would be to use a road surface that has a micro-rough structure that only causes an increased noise level inside the car.

Te Velde (1985) looked at the effect of surface roughness, where only large differences were included, for example 200 m of rough road surface and 200 m of smooth road surface. He found differences in driving speed, with lower driving speeds for the rough road surface. Van de Kerkhof and Berénos (1989) indicated that driving speed on asphaltic concrete is higher than speed on brick roads, since the surface of a brick road is much rougher than that of asphaltic concrete. Van de Kerkhof (1987) stated that roughness of a road surface is the most important factor in determining driving speed, and that it can explain 91% of the variation in driving speed. The second most important factor was the amount of buildings and the third factor was the repeating character of objects along the road side, with a more irregular character leading to lower speed. Slangen (1983) also indicates a reduction in driving speed on roads with a rough road surface (14-23% reduction).

Karan, Haas & Kher (1977) investigated the relationship between speed and road conditions for 2-lane highways. The amount of roughness was indicated by the Riding Comfort Index (RCI), that used a scale from 0 (very rough) to 10 (very smooth). A lower RCI index resulted in lower speeds. They also indicated the limitations of this finding. If the road surface is too rough, this may result in damage to vehicles and in increased accidents due to loss of vehicle control. The findings correspond with Anund (1993), who found that the speed of cars is reduced when rut depth and irregularity of the road surface increase.

Cooper, Jordan and Young (1980) found increases in driving speed of up to 2.6 km/h after resurfacing three test sites, where the profile of the road surface was improved. Te Velde (1985) investigated the effect of road surface roughness of different kinds of roads on actual driving speed. He found that if a smooth road surface was followed by a rough surface, this resulted in a mean reduction of driving speed of 5%. There was no immediate increase in speed if a rough surface was followed by a smooth road surface. Makking and De Wit (1984) found a reduction in driving speed with a transition in the road from a concrete road part to a brick one, but they indicated it is not well known if this reduction will continue after driving a brick road for a while. Sometimes this effect of speed reduction for rough road surfaces is not found, for instance in a study by Michels and Van der Heijden (1978), where no significant effect of roughness was found. This could be explained by the fact that it is very well possible that other road characteristics influenced speed behaviour in the other direction. Therefore no effect could be identified.

2.6 PERIPHERAL VISION

Research has shown that restrictions in the amount of information available in the visual periphery may lead to an underestimation of one's own driving speed (Brandt, Wist & Dichgans, 1975; Dichgans & Brandt, 1978). Salvatore (1968) had people drive in a car and provided either 25 degrees of frontal information or 25 degrees of peripheral information, at three different driving speeds. Subjects had to estimate the speed they were driving at. It turned out that 25 degrees of peripheral visual stimulation led to a more accurate speed estimation than did 25 degrees of frontal information. This can be explained by the fact that the angular velocity is much larger in the peripheral field. This finding suggests that enlarging the amount of information in the visual periphery may even lead to an overestimation in speed, possibly resulting in speed reductions.

Research by Yamanaka and Kobayashi (1970) shows that people consider speeds exceeding 2 rad/s in the visual periphery (at about 30 degrees left and right of the fovea) to be very disturbing. Road users usually choose their speed and position on the road in such a way that the angular speed of visual objects in the visual periphery does not exceed this value of 2 rad/s (Van der Horst & Riemersma, 1984; Blaauw & Van der Horst, 1982). These results seem to suggest that increasing the density of information in the visual periphery can help decrease driving speed. The lay-out of the environment should be designed in such a way that exceeding the speed limit leads to exceeding this value of 2 rad/s.

2.7 OBSTACLES

A design factor, that is closely related to lateral clearance is the presence of obstacles along the side of the road. By placing obstacles near the road side, the lateral clearance becomes smaller (Van der Hoeven, 1987). The height of the obstacles also plays a role, with the higher obstacles leading to lower driving speeds. A literature study by Tenkink (1988) indicated that speed can be influenced effectively by attaching negative consequences to speeding like discomfort, increased chance of an accident or financial consequences.

Effects of pavement width on speed were found in several studies (Kolsrud, 1985, Knoflacher and Gatterer, 1981, Lamm, 1973, Michels and van der Heijden, 1978, Lambrechts, 1985, Leong, 1968) and it seems that, in case of obstacles along the side of the road, there are only speed reductions if the presence of obstacles is combined with a reduction in pavement width. Only if the pavement width of rural roads is smaller than approximately 6 m, is there an effect of obstacles, because in that case there is less room available for lateral displacements to avoid the objects (e.g. Joycelyn et al., 1970; Tenkink, 1989). In an experiment by Tenkink (1989) the influence of three different obstacles on driving speed was investigated. For all obstacles, the space between the road and the obstacles varied between 0.68 m, 1.68 m and 2.68 m. He found that more space between the obstacle and the road side leads to higher speeds, and a more threatening object leads to a stronger reduction in speed. Drivers' reactions depend upon the kind of obstacle and the available space. For instance, the primary reaction to a small available space between the road side and the obstacle is adaptation in course. However, if more serious consequences are attached to a collision (obstacle is a tree instead of a railing), the primary reaction may be a reduction in driving speed.

Taragin (1955) also investigated the effect of obstacles on speed by putting obstacles on the highway shoulders. With two-lane highways, the reduction in speed was somewhat stronger than with four-lane highways. He used three different kinds of objects, a stationary car, a road maintenance car and a red-and-white barricade. All three objects had about the same effect on driving speed, only the barricade did not have as much effect on a 4-lane highway. On the right lane, there was a small tendency to reduce speed, although there was no specific effect on driving speed of proximity of the obstacle to the right lane. This may be the result of the presence of an emergency lane, which still left quite some space between the vehicle and the obstacle. Heavy vehicles did not reduce speed as much as did normal cars.

Besides the actual speed reduction, some attention must be paid to other safety aspects as well. Reducing speed may increase safety, but if the carriageway width is so small that there is no safe distance between the car and the obstacle, this may decrease safety again. On motorways, drivers tend to keep about 1.5 m between the car and an obstacle, so the first reaction to an object near the road side is a lateral displacement. This displacement should not cause any problems for traffic in adjacent road lanes.

2.8 RUMBLE STRIPS

A rumble strip is a strip with a rather rough texture, that can be placed on the road in either a lateral or a transverse direction. Driving on these strips produces noise and vibrations so driving comfort is decreased. The higher the speed, the larger the amount of discomfort.

In addition to the use of transverse road markings, an extra reduction in driving speed can be found when using transverse rumble bars. Zaidel, Hakkert and Barkan (1986) found that transverse rumble strips result in lower approach speeds than road markings. This effect results in uniform and moderate transitions in driving speed and this effect remains stable after a year. The disadvantage of transverse rumble strips is that they cannot be avoided, resulting in an increased noise level even at low speeds. Noordzij (1996) emphasises the possibility of using transverse rumble bars to indicate dangerous locations, like intersections and crossings. These rumble bars result in speed reductions and a decrease in the amount of crashes. In an experiment by Kermit and Hein (1962), rumble strips consisted of a number of transversely spaced overlays, placed on a road with 15-30 m between the rumble strips. Their study, that took four and a half years, investigated the effect on driving speed and in all cases (3 different junctions) the number of accidents decreased. There were significant reductions in the mean speed even after having reached only the first 3 rumble strips. Decelerations were more gradual than without rumble strips and drivers start to decelerate earlier.

A large project, commissioned by Rijkswaterstaat Drenthe investigated speed reducing measures for 80 km/h roads, without reducing driver’s comfort too much at speeds under 80 km/h. Part of this study was carried out by Van der Horst and Hoekstra (1992), who conducted a driving simulator experiment. Their idea was that negative consequences for high speeds only work, if these consequences are consistent and realistic, detectable and can be recognized and verified easily. One must keep in mind that with an increased threat, insecurity or mental stress, speed will decrease, but safety may decrease also. Therefore, speed reducing measures must be chosen with care. The measures that were chosen in this experiment were a decrease in lane width (2.25 m compared to 2.75 m), placing of rumble strips along the side of the road (one with a continuous profile, one with a rumble strip every 5 metres and one every 10 metres), 0.30 m wide centre line markings (instead of 0.10 m wide) to allow anticipation on the course of the road and reminders of the speed limit of 80 km/h every 500 m along the road side. The rumble strips along the side of the road did not provide any visual guidance, since that might lead to an increase in speed. The centre line markings also contained the rumble profile. Van der Horst and Hoekstra found that if people are instructed to be in a hurry, people drove about 15 km/h faster than when they were not in a hurry. The reduction in lane width had a significant effect on all drivers, but especially on drivers in a hurry. With reduced lane width, continuously profiled markings caused the largest speed reduction. The most direct feedback with the largest discomfort gave the best result. After driving the simulator for a while, people tended to increase their speed, but the speed on the lane with reduced width increased the least. However, the number of line crossings increased, especially in bends, so there were no serious implications for safety as long as there was enough space available aside the road to cross the lines. In summary, in this experiment the best results were found with a narrow lane of 2.25 m wide, with some extra space available aside the lane of 0.70 m, required for trucks and buses anyway, and the rumble strips with the continuous profile.

Not all studies, evaluating rumble strips found effects on driving speed. Cheng, Gonzalez and Christensen (1994) and Ribeiro and Seco (1997) investigated the effect of transverse rumble strips in close proximity of pedestrian crossings. There were no reductions in driving speed, but the rumble strips seem to improve traffic safety by working as an alerting device.

2.9 CURVATURE

The amount of curvature on roads affects speed in a number of ways. First of all, driving through curves requires extra effort in lane keeping. In addition, curves result in a reduction in the visibility distances along the road axis, limiting anticipation of the course of the road and upcoming traffic situations, leading to higher uncertainty about the course of the road. Several studies found a significant relationship between driving speed and visibility along the road axis, where reduced visibility resulted in reduced driving speed (Marconi, 1977; Bald, 1987; Brenac, 1989; Michels & Van der Heijden, 1978). Several researchers point out that road curvature mainly predicts the amount of speed reduction, but does not predict actual driving speed (Kanellaidis, Golias & Efastathiadis, 1990; Reinfurt, Zegeer, Shelton & Newman, 1991). Yagar and Van Aerde (1983) indicate that there is only an effect of visibility along the road axis with visibility distances less than 500 m. Although Taragin (1954) found a close linear relationship between operating speed and the degree of curvature, curvature had a much greater effect on speed than sight distance. This was confirmed by McLean (1979), although Watts and Quimby (1980) claim the opposite. The minimum sight distance was not necessarily related to degree of curvature, but curves of larger radii did tend to have longer sight distances.

People often underestimate the sharpness of the curve and enter the curve with a speed that is too high, requiring abrupt braking behaviour inside the curve. In a simulated driving task, Shinar, McDowell and Rockwell (1974) found that subjective judgements of curve characteristics bear little relationship to the physical characteristics of curves. Riemersma (1988b) found that three subjective counter parts of distance, radius and deflection angle of curves were not related to the objective characteristics on a one-to-one basis. This suggests that curve radii should not just be based on design speed of that particular road, but that subjective judgements should also be taken into account.

Tenkink and Van der Horst (1991) showed that with tight curves, the amount of speed reduction drivers disposed was not sufficient to maintain the amount of line crossings at a low level. This indicates people do not reduce the speed as much as would be necessary in order to guarantee safety. Advisory speeds, in comparison to general speed signs work fairly well in changing driving speed. Tenkink (1988) states that advisory speeds near curves work very well, but only if the reason for the advisory speed is explained. This is confirmed by Webb (1980), who found that when the reason for a speed restriction is not understood, advisory speed limits have only a marginal effect. Road users have to understand the reason for the warning or the restriction. Marconi (1977) found that advisory speeds work to some extent, in that they result in a more optimal traffic flow, but the reductions in speed are not always as large as aimed for. Rutley (1975) found that indicating the maximum speed at which drivers could comfortably negotiate a bend led to a mean speed closer to the advisory speed given by the sign. Drivers with low speeds increased their speed and drivers with high speeds decreased their driving speed towards the advised speed. Therefore, advance warnings for curves should be provided. Zwahlen (1987) suggests that warning signs should be placed before the beginning of the curve approach. Road markings and signs on the road surface are particularly helpful for improving safety in curve negotiation. Milosevic and Milic (1990) found that a warning sign and a speed limit sign helped drivers adjust their speed at the central point of a small radius curve more accurately.

A method of increasing driving safety at tight curves by means of road markings could be to introduce an “illusive curve phenomenon” (Shinar, 1977). This road marking provides an image of a sharp curve, so drivers anticipate the curve more appropriately. Reinfurt et al. (1991) emphasise that although low cost measures like signing, marking and delineation are attractive measures in an attempt to reduce driving speeds in curves, they cannot make up for intrinsic deficiencies of a poorly designed curve.

2.10 RISING AND FALLING GRADIENTS

Rising and falling gradients affect driving speed (Duncan, 1974; Marconi, 1977; Brenac, 1989), and work somewhat in the same way as the amount of curvature. Both road features affect visibility. Duncan (1974) indicated that gradients and curvature are the most important determinants of driving speed. With rising gradients, the visibility distance is restricted, which makes anticipation of the course of the road and upcoming traffic situations difficult. This increases drivers’ uncertainty, leading to lower speeds. There is also an influence of gradients on driving speed that is not really related to restricted sight distances. While going uphill, speed decreases due to the gravity and when going downhill, gravity causes drivers to increase speed. Usually, drivers do not compensate for these changes in speed. This may lead to dangerous situations, since this increases the differences in driving speed between traffic travelling downhill or uphill in the same direction. Variation in driving speed increases the chance of collisions (driving in fast downhill and meeting slower traffic at the bottom of a rising gradient) and deteriorates traffic flow. For this reason, the combination of strongly rising and falling gradients should be avoided to guarantee a stable traffic flow and a constant level of driving safety.

3 DISCUSSION AND CONCLUSIONS

In this literature review, the advantages and disadvantages of various speed reducing measures were identified. This review emphasises the benefits of measures other than law enforcement and traffic calming, since these measures have some important disadvantages.

Police control is only effective if drivers know that they are violating the speed limit and if they know there is a serious chance that they are being monitored. Enforcement is expensive and if a speed limit is not in correspondence with the road lay-out, enforcement does not really change the driver's attitude towards the speed limit, since they feel they are being forced to drive at a lower speed and would not choose this speed voluntarily.

Adaptations in road design can influence driving speed in various ways. Traffic calming, like speed humps and road narrowings, are fairly effective in reducing driving speeds in urban areas. However, some negative side effects have been found, like decreased driving comfort at low speeds, abrupt braking patterns and increased noise levels.

Driving speed can be reduced by providing a warning signal to drivers, that alerts them for an upcoming dangerous location. This can be done by using transverse road markings or transversely placed rumble strips. If the markings or rumble strips increase in number while approaching the dangerous location, this usually leads to an extra reduction in speed, since this creates the illusion one is accelerating. However, the effect strongly decreases over time and may even disappear. Advisory speeds can also serve as a warning, but they will only lead to actual speed reductions if drivers understand the reason for this warning.

Another way to reduce driving speed is by means of decreasing visibility distances. This way driver's uncertainty is increased and in order to achieve better anticipation, they have to slow down. This decreased visibility distance can be achieved by increasing the amount of curvature, rising and falling gradients, buildings and overgrowth. Disadvantages of these measures should be taken into account, for example driving safety could decrease when people do not reduce their speed as much as required. Therefore, it would be wise to combine measures like these with for instance road markings or transverse rumble strips to warn drivers to slow down.

A rather effective way to reduce driving speed is to decrease driving comfort for higher speeds. Road pavement treatments use this principle as well, but the problem with such measures is that they also increase driving discomfort for relatively low speeds. The best way to apply the principle of decreasing comfort would be to decrease driving comfort only for drivers that are actually exceeding the speed limit. Rumble strips, placed longitudinally on the road are rather effective in reducing driving comfort for high speeds. Drivers will try to avoid these strips, something that requires more accurate lane keeping, which is usually only possible with decreased driving speed. The rumble strips should be chosen in such a way that avoiding the strips is possible when driving at the posted speed limit. Other measures that influence driving speed via driving comfort are roughness of the road surface and the amount of peripheral information. If the road surface contains a certain level of roughness, higher speeds will lead to more vibration and noise. Increasing the amount of information in the visual periphery so that angular velocity in the peripheral field of view exceeds 2 rad/s will lead to speed reductions, since drivers will try to avoid such values due to the experienced visual discomfort.

Most road design adaptations, as discussed before, lead to the best speed reducing results if they are combined with other adaptations in road design. This way, speed reductions can be larger since the measures work in the same direction.

By providing drivers with the idea of an increased risk for high speeds, driving speeds can also be reduced. Optimally, perceived and actual risk should be related to one another. Reducing road width requires accurate steering behaviour and increases the perceived risk of running off the road or hitting other vehicles. Placing obstacles along the side of the road works much in the same way, increasing the risks of running off the road and requiring improved lane keeping. The problem with these measures is that they also increase the risk and severity of accidents involved with high speeds, which might reduce the positive effect of speed reductions. Therefore extra precautions should be taken to minimise the consequences in case a driver actually leaves the road or hits an object, or to influence the perceived risk only, for instance by reducing lane width without reducing pavement width.

At present, the most effective speed reductions are found for speed reducing measures that directly restrict the possibility to drive at high speeds. Reduced road width, speed humps, curves and rough road surfaces simply do not permit high speeds. However, these measures in themselves may have a negative effect on safety and on driving comfort.

An optimal design would be a road that leads to the appropriate driving behaviour without decreasing traffic safety. Perhaps a more effective way to reduce driving speed is to adjust the road lay-out in order to match the driver's image with the speed limit. This way drivers believe that speeding is not appropriate and they do not feel they are forced to decrease their speed but instead show the appropriate speed behaviour voluntarily.

This may be achieved by the concept of Self-Explaining roads, or roads that explain by their lay-out what driving behaviour is expected from road users. In order to explain what category the road is part of, Self-Explaining roads should be designed in accordance with the subjective road categories and use knowledge on the effect of design characteristics on subjective road categorisation. Explaining what category the road belongs to may lead to more appropriate driving speeds. If the lay-out of the road explains on what road category the driver is driving and what driving behaviour is expected, unintentional speeding may disappear. In that case, if speeding occurs, this is a conscious decision and enforcement may be appropriate. Although there has been some research on which road design characteristics contribute to subjective road categorisation, the exact relationship between Self-Explaining Roads and driving behaviour has not yet been established. In the framework of the MASTER project, this relationship will be investigated. By means of driving simulator experiments, the effects of road design and categorisation of road environments on driving speed will be established.

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