Summary, discussion and general conclusions

In this thesis, the main focus was on assistive devices that may improve and prolong the safe mobility of older drivers. Older drivers form a group of road users that is getting more and more attention in road safety research and policy. An important reason for this growing interest is the increase in the percentage of older people in the future population of most developed countries (OECD, 2001). Furthermore, the number of older drivers will increase as a result of the increasing percentage of driving licence holders among the older adults, and senior drivers continuing to drive actively longer than before (Hakamies-Blomqvist, Sirén, & Davidse, 2004; Jette & Branch, 1992). The attention for older drivers is also based on a concern for the road safety implications of a growing population of older drivers. Especially since several studies have indicated that the fatality rate of older drivers is above average; as a group their number of road fatalities per kilometre driven is higher (see e.g., Davidse, 2000; Maycock, 1997; OECD, 2001). Without countermeasures taken, an increase in the total number of road fatalities is a realistic scenario. The research presented in this thesis focused on measures that reduce crash involvement by making the driving task easier. Two types of measures were studied in detail: adjusting road design to reduce the complexity of traffic situations, and in-car devices that assist the driver. Both are considered assistive devices that have the potential to improve road safety as well as resolve the activity limitations and participation restrictions to which age-related functional limitations may lead.

The main research questions of this thesis related to a general description of the current and future safety of older drivers, the characteristics of older drivers that may influence their safety, the most important needs for support that result from these characteristics, and assistive devices that may provide the desired support.

This chapter starts with a summary of the answers to these questions. First, a concise description is given of the current safety of older drivers and the characteristics of older drivers that may be of influence on that safety. After that, the main conclusions are given on the most promising assistive devices for improving the safety of older drivers. Theoretical models played an important role in determining which assistive devices would be needed to improve the safety of older drivers. In the third section of this chapter, their
role is evaluated. The fourth section deals with a methodological aspect, the use of a driving simulator to determine the effects of assistive devices on driving performance and workload of older drivers. In the fifth and last section, measures are described that are complementary to the measures that played the leading role in this thesis.

A concise description of the safety of older drivers

In the Netherlands, the fatality rate of drivers aged 75 and above is the largest of all drivers (Chapter 1). Their injury rate is the second highest, after those aged 18-24. As in other developed countries, the high fatality rate of older drivers is mainly the result of their increased physical vulnerability; they are more vulnerable to personal injury in the event of a crash. In the second place, older drivers are over-represented in multi-vehicle crashes at intersections. These crashes particularly occur when the older driver has to turn left across a lane of traffic (turn right in left-driving countries). Not only are older adults over-involved in such crashes, they are also significantly more frequently legally responsible for those crashes, often because they failed to yield. The consequences of these crashes, in which the older driver’s car is typically hit with high speed by a vehicle coming from the driver’s side, are often serious, particularly for the older driver. The latter being the result of the point of impact as well as the increased vulnerability of older people.

The over-involvement of older people in crashes has been associated with age-related declines in visual and cognitive functions. There are few indications that a decline in visual and cognitive functions as part of normal ageing has negative road safety consequences. Only in the case of moderate and severe visual and cognitive limitations resulting from age-related disorders and diseases such as eye disorders and dementia does the relation between functional limitations and crash involvement become visible (Chapter 2). Whatever the nature of the functional limitations, their final common effects are often quite similar: an increase in the time needed to prepare and execute a driving manoeuvre and a decreased ability to perform different activities in parallel (Brouwer & Ponds, 1994).

Although significant functional limitations affect only a small part of the population, this part is expanding and will continue to do so in the next few decades. In the Netherlands, the number of people aged 65 and above will increase from 2.3 million in 2006 to 4.3 million in 2040 (Statistics Netherlands,
In comparison with the total size of the population, the share of those aged 65 and above will increase from 14.3% in 2006 to 25.0% in 2040. A substantial part of this group will be much older than 65. At this moment in time, approximately 1.1 million people are older than 74. Statistics Netherlands (2006) expects that this number will have doubled by 2040, resulting in 2.2 million people aged 75 and above. Especially in the latter age group, the percentage of people having difficulties in traffic due to functional limitations is quite large (Chapter 3).

The conclusion of the first three chapters of this thesis is that the factors associated with the safety of older drivers in the Netherlands are similar to those described in the international literature (see e.g., Hakamies-Blomqvist, 1993, 1994a; Langford & Koppel, 2006; McGwin & Brown, 1999; Nagayama, 1992; OECD, 1985, 2001; Zhang, Fraser, Lindsay, Clarke & Mao, 1998). The question remained, however, which assistive devices would be most effective in improving their safety without sacrificing their mobility.

**Assistive devices: demand and supply**

The question of which assistive devices are able to improve road safety is usually answered by looking at the available devices. This is especially the case for in-car driver assistance systems. In this thesis, however, the above question was answered by looking at the demands. In order to identify the older driver’s most important needs for support, a theoretical analysis was conducted of the strengths and weaknesses of the older driver (Chapter 4). It was assumed that to improve the safety of older drivers, assistive devices should support their relative weaknesses by correcting or compensating for them. Moreover, these weaknesses should be relevant to road safety. The theoretical analysis resulted in a list of the relative weaknesses of the older driver and the difficulties that older drivers encounter in traffic as a result of these weaknesses. In order to rate the relevance of these weaknesses to road safety, the weaknesses were compared with crash data. Those weaknesses that have a substantial influence on road safety, as indicated by the percentage of crashes that could have been avoided if the weakness would not have existed, were considered to indicate a need for support. It turned out that these (sets of) weaknesses are: 1) reduced motion perception and contrast sensitivity, 2) restricted peripheral vision in combination with reduced neck flexibility, 3) reduced selective attention, and 4) reduced speed of processing information and decision making, reduced divided attention and reduced performance under pressure of time. Table 1 links these
Assisting the older driver

weaknesses with the driving-related difficulties they may cause, and the resulting needs for support (Chapter 4).

<table>
<thead>
<tr>
<th>Relative weaknesses</th>
<th>Driving-related difficulties</th>
<th>Needs for support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrast sensitivity and motion perception</td>
<td>Difficulty reading signs and in-car displays, and difficulty with depth perception, judging the movement of fellow road users and estimating their speed</td>
<td>Draw attention to (speed of) approaching traffic</td>
</tr>
<tr>
<td>Peripheral vision and flexibility of head and neck</td>
<td>Overlooking other road users while merging or changing lanes</td>
<td>Signal or provide view of road users located in the driver’s blind spot</td>
</tr>
<tr>
<td>Selective attention</td>
<td>Overlooking traffic signs and signals</td>
<td>Assist the driver in directing his attention to relevant information</td>
</tr>
<tr>
<td>Speed of information processing, divided attention, and performance under pressure of time</td>
<td>Reaction time increases as the complexity of the traffic situation increases</td>
<td>Provide prior knowledge on the next traffic situation</td>
</tr>
</tbody>
</table>

Table 1. Most important needs for support, and the weaknesses and driving-related difficulties that create them.

Assistive devices that appear to fit the most important needs for support are summarized in Table 2. A distinction is made between road design elements that allow for the weaknesses of the older driver (Section 5.3), and in-car devices that assist the driver (Chapter 7).

<table>
<thead>
<tr>
<th>Relative weaknesses</th>
<th>Relevant road design elements</th>
<th>In-vehicle assistance systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrast sensitivity and motion perception</td>
<td>Assistance for turning left</td>
<td>Collision warning systems for intersections</td>
</tr>
<tr>
<td></td>
<td>Contrast of pavement markings</td>
<td>Automated lane changing and merging systems</td>
</tr>
<tr>
<td></td>
<td>Design of traffic signs and signals</td>
<td>Automated lane changing and merging systems</td>
</tr>
<tr>
<td></td>
<td>Design of street-name signs</td>
<td>Blind spot and obstacle detection systems</td>
</tr>
<tr>
<td>Peripheral vision and flexibility of head and neck</td>
<td>Angle at which streets meet</td>
<td></td>
</tr>
<tr>
<td>Selective attention</td>
<td>Placement of traffic signs</td>
<td>In-vehicle signing systems</td>
</tr>
<tr>
<td>Speed of information processing, divided attention, and performance under pressure of time</td>
<td>Angle at which streets meet</td>
<td>Special intelligent cruise control</td>
</tr>
<tr>
<td></td>
<td>Lane-use control signs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Type of intersection (roundabouts)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Placement of traffic signs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fixed lighting</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Road design elements and in-vehicle assistance systems that appear to fit the needs of the older driver.
Regardless of the type of assistive devices – adjustments to road design or in-car driver assistance systems – the suggested devices have hardly been tested yet on their effects on workload for and driver performance of older drivers. Exceptions are recent experiments by Shechtman et al. (2007) and Classen et al. (2007) in which the effects were evaluated of some of the adjustments to intersection design proposed by Staplin, Lococo, Byington, and Harkey (2001; see Table 2), and evaluations of the effects of the use of ITS by older drivers in the EDDIT-project (Oxley & Mitchell, 1995), in a study by Entenmann et al. (2001), and in a study by Caird et al. (2006).

Effects on workload and safety: results of a simulator study

In this thesis, the effects of both adjustments to intersection design and functions of a simulated in-car assistance system were evaluated in a driving simulator. As regards adjustments to road design, the effects were tested of different types of intersection layout, priority regulation and sight distance (Chapter 6). The in-car driver assistance system that was tested (Chapter 8), was designed to support the driver in four driving-related tasks, namely recognizing the type of priority regulation, assessing safe gaps to join or cross traffic, anticipating short sight distances, and noticing deviating traffic rules of road situations (i.e., change of speed limit and one-way street). Workload was measured by performance on a secondary task, and driver performance was measured by waiting position before passing intersections, acceleration and speed while passing intersections and safety of driver decisions. The latter was measured by crashes between participants and surrounding traffic, and by the precursor of crashes, that is, deceleration of surrounding traffic in order to prevent crashes.

The results regarding intersection characteristics showed that intersection layout, priority regulation, as well as driver manoeuvres influenced the difficulty of passing intersections. Intersection layout was the best predictor of variations in workload. Three-way intersections that only had a side-street at the left-hand side of the driver turned out to be the easiest intersections to pass, whereas four-way intersections with dual carriageways were the most difficult to manage.

The results regarding the in-car driver assistance system are summarized in Table 3. All three safety-related messages increased the safety of driver decisions. Messages regarding the priority regulation, obstructed view of an intersection, and safe gaps to join or cross traffic streams led to fewer and/or
less decelerations of relevant other vehicles. The message regarding an unexpected one-way street led to fewer route-errors.

<table>
<thead>
<tr>
<th>Type of message</th>
<th>Workload (+ = higher workload)</th>
<th>Safety of driver decisions (+ = safer decisions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority regulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right of Way</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Yield to Right</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Approaching Major Road</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Safe gaps</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Short sight distances</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Deviating situation: one-way street</td>
<td>+</td>
<td>Fewer route errors</td>
</tr>
</tbody>
</table>

Table 3. Effects of in-car assistance systems.

Differential effect of functional age

As the assistive devices described above were selected based on the relative weaknesses of the older driver, it was expected that older drivers would benefit more from their support than younger drivers would. That is, it was expected that people with functional limitations will benefit more from the support provided by the selected assistive devices than people with no functional limitations. Therefore, functional age rather than chronological age was used to compare workload and driving performance between age groups. Functional age was based on scores on three tests of cognitive functioning, relating to reaction time, selective attention, and visual-motor coordination. Persons scoring well on the average of these three tests were considered to be functionally young, whereas persons scoring relatively poor on them were considered to be functionally old. People scoring in between were considered to be functionally middle-aged. Although it turned out that the majority of the chronologically older people was also functionally old, there were some exceptions. One of the chronologically old participants even appeared to be functionally young. At the same time, two of the chronologically young participants appeared to be functionally old. This underlines the importance of a personal approach in decisions about fitness to drive.
It was found that functional age affects workload as soon as people start driving. The mean reaction times of drivers of different functional age groups were the same when they had to carry out a detection task (secondary task) while they were sitting in a parked simulator car. However, when performing the same task while driving (primary task), functionally older drivers had longer mean reaction times than both functionally young and middle-aged drivers. As traffic situations got more difficult as a result of changes in the intersection design, the workload of all drivers increased further. However, this increase in workload did not increase with functional age. An interaction effect was only established for the increased effort needed to combine the primary and secondary task. In that case, functionally older drivers experienced a higher increase in workload than younger drivers did.

Driver support as offered by the in-car driver assistance system did not reduce workload. To the contrary, messages regarding the approach of a major road and messages regarding an unexpected one-way street even led to an increase in driver workload as indicated by reaction times on a secondary task (see Table 3). Interaction effects of driver support and functional age were not established.

Whereas functional age did affect workload, this age effect was not established for safety of driver decisions. All age groups appeared equally capable of deciding whether it was safe to cross or join other traffic streams, regardless of the difficulty of the intersection design. As regards the effect of the driver support system on safety of decisions, it was found that all safety-related messages increased the safety of driver decisions for all age groups. The only interaction effect that was established concerned messages regarding an obstructed view of the intersection. Functionally middle-aged participants appeared to profit the most from these messages.

The fact that functional age only affected workload and not safety of driver decisions, and that no interaction effects were found between functional age and intersection design, can be the result of three related matters. First of all, it may indicate that our functionally older drivers were capable of adequately compensating for their increased reaction time. Another explanation may be that our simulator environment did not sufficiently put our drivers to the test. Perhaps task demand should have been higher to overask the capabilities of the functionally older driver and affect the safety of his decisions. On the other hand, our functionally older drivers may have
been too young. After all, they were people who still drove on a regular basis and did not have considerable functional limitations. Therefore, future studies investigating the differential effects of intersection design on driver behaviour of older and younger drivers should include drivers with more severe functional limitations and confront them with traffic situations that are more difficult to pass.

User acceptance

Having a positive effect on the safety of driving behaviour is only one of the preconditions for in-car driver assistance systems to be successful in improving the safety of a specific group of road users. To obtain that goal, driver assistance systems should also be used and trusted, and the information that it provides should also be understood by its users (Chapter 7). Therefore, the evaluation of the in-car driver assistance system described in this thesis also included user acceptance testing. The results of these tests showed that drivers were moderately positive about the usefulness of messages regarding priority regulation, obstructed views of the intersection, and deviating traffic rules or road situations, and neutral about the usefulness of messages regarding safe gaps to join or cross traffic. In general, drivers were not as positive about the satisfaction the messages gave as they were about their usefulness. They were actually a bit negative about this aspect of the messages. The actual experience with messages regarding priority regulation and deviating traffic rules resulted in more positive opinions about the satisfaction these types of messages give (Chapter 8).

Returning to the opinions about the hypothetical systems as they were described to the participants before they had experienced them, it turned out that functionally old drivers were more positive about the usefulness and satisfying character of messages regarding safe gaps to join or cross, obstructed views of the intersection, and deviating traffic rules or road situations (different speed limit, one-way street), but were as positive about the usefulness of messages regarding priority regulation as the other age groups. Similarly, participants who had more disorders, or who had difficulties with more manoeuvres or who would like to have assistance with several manoeuvres were more positive about the hypothetical assistance systems than participants without any disorders, difficulties or desire for assistance. After the actual experience with the support system, opinions changed and age differences seemed to disappear. Younger drivers tended to become more positive while older drivers tended to become less positive.
Some of these findings are not consistent with those of other studies (e.g., De Waard, Van der Hulst, & Brookhuis, 1999; Viborg, 1999). As discussed in Chapter 8, this can be caused by differences in the types of messages which were sent to the drivers (driving too fast vs. driving too slow) and by regression to the mean.

As regards the willingness to buy the system that was “installed” in the simulator car, 35% of the participants indicated that they were willing to buy the system if it were on the market. Half of them was willing to pay for it. Most participants were positive about the audibility and comprehensibility of the messages. Except for one participant, everyone was very well able to hear the messages. Eighty-five per cent of the participants indicated that the messages were also easy to understand and that it was easy to act upon them. This does not mean that they always did act upon them. Only 18% said that they always followed the advice of the support system. Another 63% frequently followed the system’s advice. One of the reasons for not following the system’s advice may be that participants did not always trust them. Thirty-five per cent of the participants trusted the advices only occasionally or never. Two participants indicated that it depended on the type of messages; they always trusted information about traffic rules, but never about safe gaps to join or cross.

Summary of main findings

As regards the safety of older drivers in the Netherlands, it was found that:
- The fatality rate of drivers aged 75 and above is the largest of all drivers in the Netherlands.
- The high fatality rate of older drivers is mainly the result of their increased physical vulnerability.
- Older drivers are over-represented in crashes at intersections and more often legally responsible for these crashes, often because they fail to yield. These crashes particularly occur when the older driver has to turn left.
- In general, there are few indications that a decline in visual and cognitive functions as part of normal ageing has negative road safety consequences. Most drivers can compensate for these declines. In case of moderate or severe functional limitations due to age-related disorders and diseases, older drivers need more time to prepare and execute a driving manoeuvre and have more difficulties performing different activities in parallel.
Assisting the older driver

- The current number of inhabitants aged 75 and above in the Netherlands will be doubled by 2040, resulting in 2.2 million people of that age.
- The number of older drivers will not only increase because of the ageing of the population but also because of an increase in the percentage of licence holders among older adults in general, and older women in particular.

The fatality rates of older drivers can be influenced in various ways. The main focus of this thesis was on measures that reduce crash involvement by making the driving task easier. Two approaches were studied in more detail: adjusting road design to reduce the complexity of traffic situations, and in-car devices that assist the driver.

With regard to road design it was found that:
- Older drivers are more often involved in crashes at intersections at which traffic is regulated by means of yield signs than they are at intersections at which traffic is regulated by means of traffic lights.
- Adjustments to road design that appear to be particularly beneficial to older drivers include a positive offset of opposite left-turn lanes, high in-service contrast levels for road markings, long sight distances, advance warning signs, and conversion of intersections into single-lane roundabouts.
- Intersection layout, priority regulation, as well as driver manoeuvres influence the difficulty of passing intersections.
- Intersection layout is the best predictor of variations in workload. Three-way intersections that only have a side-street at the left-hand side of the driver are the easiest intersections to pass, whereas four-way intersections with dual carriageways are the most difficult to manage.
- A reduction in the complexity of intersections leads to shorter reaction times for both functionally old and functionally young drivers. Therefore, adjustments to road design that reduce workload for older drivers will also be beneficial for younger drivers.

With regard to in-car driver assistance systems it was found that:
- Collision warning systems for intersections, in-vehicle signing systems, special intelligent cruise control, and systems that provide information on the characteristics of complex intersections the driver is about to cross appear to have the most potential to improve the safety of older drivers. However, many of these systems are still being developed and
not much research has been done on user acceptance and effects on road user behaviour.

- Messages regarding priority regulation, obstructed view of an intersection, and safe gaps to join or cross traffic streams increase the safety of driver decisions for all age groups. Informative messages regarding unexpected one-way streets lead to fewer route-errors. These messages are currently not provided by existing ADAS such as ACC or navigation systems, but they could possibly be added to them in the future.

- Contrary to expectations the abovementioned messages did not reduce workload; some even increased driver workload. As this is probably the result of the new task that was added to the driving task (listening to and processing the information offered by the assistance system), it is expected to wear off over time.

- Functionally old drivers were initially more positive about the usefulness and satisfying character of most of the messages that were specifically designed for them than the younger age groups were about these same messages. However, after having experienced them opinions changed and age differences disappeared.

- Drivers who have more disorders, have difficulties with more manoeuvres, or would like to have assistance with several manoeuvres were more positive about the abovementioned messages than drivers without any disorders, difficulties or desire for assistance.

- Whereas the majority of the functionally young drivers considered the timing of messages to be correct or even found that messages came too soon, most of the functionally old considered them to come too late. Therefore, system settings should be adjustable.

### Implementation in the real world

**Road adjustments and/or in-car driver assistance?**

A (policy) question may be which kind of assistance would be preferable: adjustments to road design or in-car assistance systems. In my opinion, the answer should be that they complement each other and that both types of measures should be taken. Although the adjustments to road design have been selected for their capacity to increase the safety of older road users, they will also make a contribution to the safety of other road users. Measures that give the driver more time to observe things and to base decisions on these observations make the driving task easier for all road users. The reduced
complexity of the driving task will probably reduce the number of human errors, and in the end possibly also the number of crashes. The fact that road adjustments that benefit older road users also have (smaller) positive effects on the safety of other road users, is an additional argument for taking such measures (Chapter 5). Furthermore, the proposed adjustments fit in with the principles of a sustainable safe traffic system (see Wegman & Aarts, 2006), which is the current practice in road safety policy in the Netherlands. However, there is probably a cut-off point below which a task becomes so easy that some drivers will start showing risk compensation, for example by means of speeding (Evans, 1991; Wilde, 1982). Therefore, there will be a limit to easing the driving task by way of road adjustments. For those drivers that need extra or more specific help, an in-car assistance system can adjust the driving task to the possibilities of that individual driver. Moreover, it is imaginable that some functional limitations require assistance which cannot be given by way of road adjustments. As a result, in-car driver assistance systems offer an extra opportunity to prolong the safe driving career of older people, without creating a road infrastructure that is ‘too easy’ for other road users.

On the other hand, whereas it was concluded in Chapter 7 that only very few of the in-car driver assistance systems that appear to be most beneficial to the safety of older drivers are currently available, adjustments to road design can readily be implemented as long as there is the money and the opportunity (i.e., new roads, maintenance of existing roads) to do so. Nevertheless, it appears that there is an increase in the number of initiatives to develop systems that are especially designed for the older driver and to improve the design of existing systems to allow for the functional limitations of the older drivers. Moreover, recent developments appear to fit in with the systems that are expected to be the most promising ones from a road safety point of view (Table 2). One example is a system that Nissan is currently testing. This Japanese car manufacturer has announced a 30-month experiment, which started in October 2006, in which several functions will be tested, among which a "vehicle alert" which tells drivers that another vehicle is moving too fast at an intersection at which buildings and/or trees obstruct the drivers’ view of cross traffic. In this situation a voice message warns the driver: "Car approaching from left (or right)". Nissan hopes to commercialise the system by 2010 (New Scientist Tech, 2006). The "vehicle alert"-function is comparable to the alert for short sight distances and a good substitute for the "safe to join or cross"-function of the system which was tested in Chapter 8. The other functions tested in Chapter 8, messages regarding priority
regulation and regarding deviating traffic rules and situations, can probably be included in navigation systems. Entenmann et al. (2001) have carried out a pilot-study to explore the possibilities of adding design-related information such as priority regulation to digital maps, and it turned out that it was technically feasible to collect and digitise this kind of information (Chapter 7).

**Prerequisites for success**

The conclusion of the above is that in-car driver assistance systems can potentially prolong the safe mobility of older drivers. A drawback of these systems is, however, that whereas they are deployed to simplify the driving task, reduce workload and improve safety, using them may actually increase workload and have negative safety consequences as well. This may be the result of an improper design of the system’s human-machine interface (HMI), the installation of several independent systems in one car, or loss of situation awareness due to complete automation of one part of the driving task which may place the human out of the continuous cycle of perception, decision making and action (Chapter 7). As Heijer et al. (2001) have indicated, the latter threat may be taken away by letting ADAS support the driver instead of replacing him. The second threat, several independent systems in one car fighting for the attention of the driver, may be averted by including a mediating system which decides when which system is allowed to pass what kind of information in what kind of way (see e.g., Montanari et al., 2002; Piechulla, Mayser, Gehrke & König, 2003; Vonk, Van Arem & Hoedemaeker, 2002; Wheatley & Hurwitz, 2001). In order to prevent that a poorly designed HMI nullifies the potential safety effect of an in-car driver assistance system, the design of this interface should allow for the functional limitations of the older driver. Those design principles that are relevant to the functional limitations of older drivers have been summarized in Table 4. Note that these principles are relevant for not only the design of the HMI of in-car driver assistance systems, but also for the design of specific road elements such as legibility of street name signs, contrast of road markings, and placement of road signs (Chapter 5).
<table>
<thead>
<tr>
<th>Functional limitations</th>
<th>Relevant design principles</th>
</tr>
</thead>
<tbody>
<tr>
<td>General sensory deficits</td>
<td>Use redundant cues, like auditory, visual and tactile feedback.</td>
</tr>
<tr>
<td>Visual acuity</td>
<td>Increase character size of textual labels on traffic signs and in-vehicle displays.</td>
</tr>
<tr>
<td>Colour vision</td>
<td>Use white colours on a black background for in-vehicle displays.</td>
</tr>
<tr>
<td>Night-time visual acuity</td>
<td>Use supplemental illumination for in-car devices used in low-light conditions, retro reflective road signs, and fixed lighting at intersections with high traffic or pedestrian volumes.</td>
</tr>
<tr>
<td>Sensitivity to glare</td>
<td>Use matt finishes for control panels and antiglare coating on in-vehicle displays, and reduce the intensity of traffic signals during darkness.</td>
</tr>
<tr>
<td>Hearing</td>
<td>Use auditory signals in the range of 1500-2500 Hz range.</td>
</tr>
<tr>
<td>Contrast sensitivity and motion perception</td>
<td>Where depth perception is important for information on in-vehicle displays, provide non-physical cues, such as relative size, interposition, linear position and texture gradient. As regards road design, use a minimum in-service contrast level of 3.0 for pavement markings, background plates to help accentuate traffic lights, and a positive offset of opposing left-turn lanes.</td>
</tr>
<tr>
<td>Selective attention</td>
<td>Enhance the conspicuousness of critical stimuli through changes of size, contrast, colour or motion.</td>
</tr>
<tr>
<td>Perception-reaction time</td>
<td>Give the user sufficient time to respond to a request by the in-vehicle assistance system and provide advanced warnings to provide the driver with enough time to react to the on-coming traffic situation. As regards road design, this can be accomplished through multiple or advance traffic signs.</td>
</tr>
<tr>
<td>Hand dexterity and strength</td>
<td>Use large diameter knobs, textured knob surfaces and controls with low resistance.</td>
</tr>
</tbody>
</table>

Table 4. Functional limitations and relevant design principles for road design elements and in-vehicle displays (based on Caird et al., 1998, Gardner-Bonneau & Gosbee, 1997, and Staplin et al., 2001).
Value of the theoretical framework

Theoretical models played an important role in determining which assistive devices would be needed to improve the safety of older drivers. Assuming that to improve the safety of older drivers, assistive devices should support their relative weaknesses, a theoretical analysis was conducted of the strengths and weaknesses of the older driver. The theoretical framework that was used to identify the relative weaknesses of the older driver included Fuller’s task-capability interface model, ideas that originate from the human factors approach, cognitive psychological models, and game theory (Chapter 4). Fuller’s task-capability interface model (2001) has the advantage that it integrates the physical, cognitive, motivational and social factors of road users as well as the vehicle and environmental factors into one conceptual framework. As a result, it provides insight into the interrelationships between these factors. It makes one realize that turning a certain wheel of the ‘system’ also has implications for the direction of another. A (substantial) decrease in the capabilities of a driver asks for a reduction of the demands posed by the traffic system. Otherwise the driving task will become too difficult, and errors are more likely to occur.

Fuller’s model also provides insight into the available ways for reducing task demands or improving capabilities: training and education (e.g., about compensatory behaviour and the influence of medication), letting the car assist the driver, adjustments to road design, and/or informing other road users about the older drivers’ possibilities and limitations. The other models included in the theoretical framework were used for putting in the details to warrant the quality of specific measures. Which strengths and weaknesses of older drivers should be taken into account while designing assistive devices for them? What are, for example, the boundaries of older adults’ information processing and what does that mean for the design of human-machine interfaces and road signs (human factors approach)? How do older drivers compensate for decreased capabilities, and what are the implications of mental schemata that trigger the appropriate action for the design of intersections (cognitive psychology)? How do decreased capabilities and the use of in-car driver assistance systems affect the interaction with other road users (game theory)? In comparison to the other theoretical models, game theory was a relatively new player in the field of road safety research. Hence, there was not much literature available on how to apply the principles of game theory to decision making and anticipating the likely reaction of others in traffic. However, the attempts made in Chapter 4 to link research results
regarding the interaction between road users with the principles of game
theory taught us that such exercises are fruitful for gaining insight into the
interaction between road users. It would be interesting to have a closer look
at some of the topics that emerged from the analysis of the strengths and
weaknesses of older drivers according to the framework of game theory.
More specifically, future studies may look at the interaction between road
users and determine whether there are age-related differences in the way
people communicate with other road users, and whether older drivers apply
different rules for communication. Are they, for instance, more inclined to
take right of way or is the opposite true and are they more inclined to yield
in case of doubt?

On a more general level, it would be interesting to determine whether the
factors that – according to Fuller’s task-capability interface model –
determine task difficulty are all equally important for all groups of road
users. Some factors may be more important for older drivers, whereas others
may be more important for younger drivers. In Section 5.2.1, it was argued
that the complexity of a traffic situation is the factor that becomes more
important as people age. Complex situations put a severe strain on the
sensory, perceptual and cognitive capacities of the driver, and these
capacities are often reduced in the older age group. For younger adult
drivers, other factors were expected to play a role in the likelihood of crashes,
such as whether or not the road layout offers drivers the opportunity to
speed, and factors like emotions, alcohol and other drugs, stress, and
distraction. Submodels are welcome that zoom in on the specific issues
relevant for particular groups of drivers. These models will be particularly
useful for designing measures that are tailored to the needs of the group in
question.

**Older people driving in simulators**

As the implementation of measures concerning road design, and the
development of prototype assistance systems are very expensive, both types
of assistive devices were evaluated in a simulated environment using a fixed
base driving simulator. Although the use of a driving simulator to evaluate
driving behaviour has several advantages over testing in the real world, such
as low costs, experimental control, and driver safety (see e.g., Kaptein,
Theeuwes & Van der Horst, 1996; Lee, Cameron & Lee, 2003; Nilsson, 1993),
it can also have disadvantages. Two potential disadvantages are the
ecological validity of the experiment and the incidence of simulator sickness.
Ecological validity

One of the major concerns in using driving simulators to measure road user behaviour is the generalizability of research results to real traffic, also known as ecological validity (see e.g., Kaptein, Theeuwes & Van der Horst, 1996; Neale & Liebert, 1986; Nilsson, 1993; Slick, Tran & Cady, 2005). To ensure the ecological validity of an experiment, the face validity or fidelity of the simulated world should be high. The driving simulator that was used for the experiments described in Chapter 6 and 8 gave us ample opportunity to design a world that resembles the real world. It allows researchers to design their own road network, to add their own types of houses, add signs and markings, and, more important, it includes self-governing intelligent vehicles that show natural and normative driver behaviour. For the experiments that were described in Chapter 6 and 8, an existing road network was used and a city was built around it, using houses, shops, trees, and ponds. The surrounding traffic was given instructions on the route they had to follow and the speed they should maintain. It was not necessary to instruct them about priority regulations, as they were able to deduce them from the design of the roads. The result was a simulator world that was just like the real world on a weekday with many people driving through the city. The comments of the participants confirmed this. They were talking to the other vehicles just like people do in real traffic, and they really felt like they were going for a drive. To give an example of the latter, one of the older participants said while entering the simulator room for her second drive “Let me first take a candy, as I always do that when I am going for a drive”.

However, there is more to ecological validity of the experimental setting than making sure that it looks real. Vehicle operation is an important element as well, especially for older drivers. Research by Lundberg & Hakamies-Blomqvist (2003) suggests that, at least for older drivers with cognitive deterioration, “the need to adapt to an unfamiliar vehicle represents a supplementary cognitive load that may compromise their driving ability and the validity of the assessment”. They concluded this after having compared the outcomes of driving tests in which people were allowed to drive in their own car with those of driving tests in which people were obliged to use the car of the driving test facility. The percentage of drivers who failed the test was significantly larger in the second group. The use of a driving simulator to study driving behaviour may have the same adverse effects. Although in our experiments people sat in a real car seat, used a force-feedback steering wheel, mechanically transmitted gas-, clutch- and brake pedals, and the
transmission of the simulator car was adapted to match the experience of the participant, the operation of the simulator car will have been different from their own car, just as driving another person’s vehicle is. In some participants, this was more evident than in others. Their engine frequently cut out due to inadequate handling of the clutch and/or their steering behaviour was inaccurate. Vehicle operation was not one of the coded variables, but (functionally) older participants seemed to have more difficulties operating the simulator car than younger participants. This fits in with the increased cognitive rigidity of older people (see e.g., Brouwer & Ponds, 1994; Brouwer, Rothengatter & Van Wolffelaar, 1988).

As the design of the experiments ensured that within-subjects comparisons were made to evaluate the effects of the assistive devices, and the order of the route across the intersections and the drives with and without the assistance system were counterbalanced, the main study results were not likely to be affected by the use of an unfamiliar (simulator) car. However, comparisons between functional age groups may have been affected. The only effect that was found for functional age group was a general effect of workload which appeared as soon as people started driving the simulator car (Chapter 6). This effect was attributed to the age-related increase in the cost of dividing attention. The size of the effect may have been exaggerated, however, by the sensory-motor secondary (or tertiary) task of adapting to an unfamiliar vehicle. Increased difficulty of driving situations and related vehicle handling did not increase the differences between functional age groups any further.

**Dropout as a result of simulator sickness**

As with ‘natural’ motion sickness, simulator sickness is caused by a mismatch between sensed and expected motion cues (Farmer, Van Rooij, Riemersma, Jorna & Moraal, 1999). In case of a fixed-base driving simulator, visual cues tell the driver that he is moving, whereas vestibular cues tell him that he is standing still. Sensitivity to motion sickness varies largely among humans. Women, for example, are somewhat more sensitive to motion sickness than men (Wertheim, 1997). Symptoms of motion and simulator sickness are: nausea, vertigo, sleepiness, cold sweats, pallor and saliva flow (Farmer et al., 1999; Moroney & Moroney, 1999). Despite extensive screening for sensitivity to simulator sickness using the Motion Sickness/Simulator Sickness Screening Form (Hoffman, Molino & Inman, 2003), simulator sickness led to a large reduction of the initial number of persons that
participated in the simulator studies described in this thesis. As much as 46% of the participants dropped out because they felt sick while driving the simulator car. High dropout rates are not uncommon. Caird (2004b) has made an inventory of simulator studies using older participants and their dropout rates. It turned out that dropout rates varied from 40 to 75%. Nevertheless, one of the concerns during the simulator studies that were described in Chapter 6 and 8 was that dropout could have affected study results, especially since dropout rates differed significantly between functional age groups (29% for young, 46% for middle-aged, and 58% for old participants). As there was one questionnaire that was filled in by all participants, both those who turned out to be sensitive to simulator sickness and those who were not, we were able to compare some of the characteristics of these two groups of participants. Apart from differences in group composition due to significantly higher dropout rates for functionally old as well as female participants, it turned out that the functionally old participants that completed all parts of the experiment tended to be more negative about the driver support system than those that only completed the first part of the experiment. This shows that simulator sickness can cause selective dropout of participants which may affect the representativeness of the sample used to test the opinions about or behavioural effects of certain countermeasures (see also Edwards, Caird, Lamsdale, & Chisholm, 2004 and Freund & Green, 2006).

To prevent this, simulator sickness should be countered by using experimental procedures that not only include screening procedures for sensitivity to simulator sickness, but also address other factors that might add to simulator sickness, such as simulator configuration (size of the screens, amount of motion cues), and general aspects of the driving environment (proximity of buildings and trees, number of turns, degrees of curvature). It may even involve reducing the fidelity of the simulated environment (see Ecological validity), as there are some indications that increased fidelity leads to a higher incidence of simulator sickness (Kennedy, Hettinger & Lilienthal, 1990). Future studies could, for example, reduce the amount of visual motion cues by introducing fog as soon as the driver has taken the decision to join or cross traffic, and put the driver in a new position on a straight road stretch before removing the fog (Van Winsum, personal communication). Another solution would be to slowly build up the amount of visual cues in the course of the drive in order to reduce the participant’s sensitivity to simulator sickness (Busscher, Van Wolffelaar & Brouwer, 2007).
Complementary measures

In previous paragraphs, various driver assistance systems and adjustments to road design were discussed that appear to improve the safety of older drivers. These types of measures are complementary to each other and it was argued that they both should be taken. Adjustments to road design and use of in-car driver assistance systems cannot prevent, however, that some road users at a certain moment in their lives will become unfit to drive. Therefore, a procedure for a timely exit from active traffic participation, when functional limitations become too severe to compensate, does remain necessary. Ideally, the decision to stop driving should be left to the drivers themselves. However, not every individual is aware of limitations in fitness to drive. For example, in the case of dementia or right hemisphere stroke, persons often do not have a clear picture of their limitations. It is, therefore, important to provide support for decisions to drive less or not at all. This applies not only to the older drivers themselves, but also to their family, and to doctors and psychologists responsible for medical examination. As argued by Brouwer and Withaar (1997) and Hakamies-Blomqvist, Henriksson and Falkmer (1998), an obligatory medical or on-road examination is only justifiable if it is restricted to patient categories with a substantially increased crash risk. To achieve such a procedure, more knowledge is needed in a number of areas. In the first place, knowledge is required about high-risk patient groups. Some high-risk groups, such as people suffering from mild dementia, have already been defined. For other disorders, more specific definitions of subpopulations who indeed form a high-risk group must be determined. Having defined high-risk groups, it is then important to apply test methods within these groups that can validly and reliably select those individuals who actually display dangerous driving behaviour. Research is needed to further develop these assessment methods. Those individuals who have been shown to display dangerous driving behaviour must then be declared unfit to drive unless aids (i.e., assistive devices or training) are available that can compensate for the functional limitations that accompany their disorder or disease. Further research is needed to develop and evaluate these aids.

If driving a car is indeed not longer a safe option, alternative means of transport should be made available to ensure the mobility of older people. Examples of alternative means of transport are conventional public transport services, bus service routes, taxis, and dial-a-ride services for door-to-door travel. No single form of transport provides mobility for all people under all
circumstances. A family of services is needed that enables travellers to select the one that best suits their requirements for a particular journey (OECD, 2001).

For those who are still fit to drive but nevertheless get involved in a crash, improved crashworthiness of vehicles and further development of safety devices are important to reduce injury severity. As regards crashworthiness, current crash-test dummies and models are based on average fit people. Test dummies capable of modelling the effects of an older occupant are needed to be able to take into account the older occupants’ frailty when testing and improving vehicle safety. In addition, occupant protection should be enhanced by further development of seat belts and airbags, particularly through force-limiting features. A safety device that is likely to be especially relevant for the protection of older drivers is the airbag that protects the head and chest in side-collisions such as crashes when turning left in which older drivers are overrepresented (i.e. side-impact protection systems).

The same group of drivers, those who are still fit to drive, can also be supported through another way of easing the driving task: by improving their driver performance through education. Training programmes provide a good opportunity for informing the older driver of the physical and cognitive changes that accompany ageing, difficulties that may arise in traffic as a result of these changes, and how to modify driving strategies to avoid these difficulties.

To acknowledge all factors that Fuller (2001) incorporated in his task-capability interface model, attention should also be paid to the other road users, that is, those who may meet older drivers in traffic. By giving them information on the difficulties older drivers experience in traffic, they may be able to anticipate better on the older drivers’ behaviour, and help to prevent future crashes.