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Integrating vehicle design and human factors: minimizing elderly driving constraints

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Abstract

With a projected rise in the number of elderly, most of whom have also relied primarily on the private automobile for their mobility, it is likely that future adaptations in vehicle design will be linked in some part to the physical infirmities often faced by the elderly. This paper offers a bridge between medical research on the physical impairments of the elderly and automobile design and driving safety. We describe recent findings on the driving-related physical and cognitive impairments faced by the elderly. We then propose two major types of vehicle design and infrastructure adaptations: (1) modifications for private vehicles, and (2) intelligent technology and support services for private vehicles, which can help to minimize the driving-related effects of these impairments. For example, we present a range of modest vehicle design adaptations for components such as seats and doorways, handles, knobs, and steering wheels, and seat belts. We find that many of these improvements can be made to standard passenger vehicles with little additional design effort, and that the adaptations should also increase overall vehicle marketability. Finally, we argue that while most, if not all, of our proposed adaptations would be made to largely benefit the elderly, they will nevertheless support and improve driving across all age groups.

Keywords: Human factors; Transportation; Elderly; Vehicle design

1. Introduction

It should be of little surprise that the US elderly population continues to grow in size and political influence. This trend has been apparent for quite some time (US DOT, 1980) and shows

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little sign of reversal until at least the year 2050 (Rosenbloom, 1995; Pirkl, 1994). By the year 2000, it is projected that 35 million people in the United States will reach the age of 65 (Pirkl, 1994). If the current trend continues, these elderly will be traveling more and experience greater reliance on automobiles than ever before, irrespective of income (Rosenbloom, 1995).

There are important consequences associated with an increased reliance by the elderly on the automobile. For instance, accident rates pose a potentially very serious problem. Currently automobile crashes are the leading cause of death from injuries for those 65–75 years old and the second leading cause for those 75 and older (Reuben et al., 1988). An inability to drive implies less mobility, particularly for the growing number of suburban elderly. For many elderly, loss of a driver's license also implies loss of personal freedom, independence, and usefulness to society (Waller, 1991).

Approximately 58% of the growing older population will acquire some form of disability (Pirkl, 1994). Increased age is associated with declines in perceptual (i.e., vision and hearing); cognitive response time (i.e., motor skills coordination); cognitive memory and attention, and physical strength and dexterity performance. Future design and technological adaptations have the potential to extend and strengthen driver confidence and performance in light of physical limitations and age. To date, however, any technological innovation addressing the elderly has relied on an individual designer's knowledge of the user and her disabilities (Kantowitz and Sorkin, 1983), rather than industry-wide understanding. There is a need to increase accessibility to information about elderly cognitive and physical driving-related impairments; this necessarily means bridging research between vehicle design and elderly health.

This paper focuses on methods for modifying vehicle design to accommodate a wide range of physical limitations. In turn, this will improve long-term use of private vehicles by the elderly. We begin with an overview of the more common physical and cognitive impairments faced by the elderly population and explore how these impairments are related to driving. We then discuss two major types of vehicle design and infrastructure adaptations: (1) design modifications for private vehicles, and (2) intelligent technology adaptations and support services for private vehicles. Finally, we conclude with recommendations for linking these technological adaptations to physical and cognitive impairments.

2. Relationship between age-related health effects and driving

In a recent literature review (Charness and Bosman 1994), the results of experimental and descriptive studies examining the nature of age-related changes in perceptual (i.e., vision and hearing), cognitive, and physical performance were used to develop qualitative thresholds for age-related impairments. However, these thresholds, while certainly useful, do little to quantify how age-related health can be incorporated into actual vehicle design standards.

To supplement the qualitative characteristics noted by Charness and Bosman, we conducted an extensive literature review to assemble quantitative details and statistics regarding changes in physical factors in five major areas of impairment: (1) vision, (2) hearing, (3) cognitive response time, (4) cognitive attention and memory, and (5) physical strength. As part of our review, we briefly discuss the compensating factors and mechanisms that seem to evolve as individuals age. The results of this review are summarized in Tables 1–3, with companion discussion below.

Table 1
Visibility

	Major trends and statistics
Visual fields	• About one in seven over 65 have abnormal visual fields (Johnson and Keltner, 1983). • Thirteen percent over 65 exhibit a field deficit; 3.5% had severe loss of visual fields; and 57.6% of those with abnormal vision were previously unaware of this condition (Reuben et al., 1988; Johnson and Keltner, 1983).
Visual acuity	• With decreasing contrast (in light), a drop in acuity is more pronounced in an elderly driver's eyes (Richard, 1966; Sivak et al., 1981). • One-third of those with decreased visual acuity, have a visual field defect; however, only 4.1% with visual field defects had decreased visual acuity (Johnson and Keltner, 1983). • Over 4% of those aged 65–74 and 12.7% of those 75 or older (7.4% are legally blind) showed a static visual acuity of 20/60 or worse (Reuben et al., 1988).
Vision field loss	• The frequency of visual field loss is 3–3.5% for individuals 16–60 years; however, visual loss is roughly 13% for people over 65 (Johnson and Keltner, 1983). • The rate of occurrence of visual field defects in those over 65 is four to five times greater than for those in younger age groups (Johnson and Keltner, 1983).
Useful fields of vision (UFOV)	• UFOV is the visual field area over which information can be acquired in a brief glance (Sanders, 1970; Ball and Owsley, 1991). Older persons tend to have smaller UFOVs than younger persons (Sekuler and Ball, 1986; Sivak, 1995). • Adults with UFOV shrinkage report more problems in everyday activities that rely on peripheral vision (e.g., driving), even though they may not experience a visual sensitivity impairment (Ball et al., 1990; Ball and Owsley, 1991). • Older drivers with substantial shrinkage in UFOV experience 4.2 times more crashes than older drivers with larger UFOV (Owsley et al., 1991; Sivak, 1995). • Brown et al. (1993) have found a weak correlation ($r = 0.05$) between UFOV and crashes (Owsley, 1994).
Peripheral vision	• The total horizontal peripheral visual field typically drops from 170° in young adults to approximately 140° by the age of 50 (Retchin et al., 1988). • Data from Burg (1968) show that the lateral peripheral vision field decreases by about 17 total degrees between the ages of 22 and 67.
Glare/night legibility	• Among the elderly, the physiological basis of glare impairment is due to the gradual degeneration of the eye lens, which degrades image contrast and the ability of the eye to see low-contrast objects at night (Pulling et al., 1980). • Older drivers are more susceptible to temporary visual impairment from headlight glare (Wolf, 1960; Pulling et al., 1980). McCloskey et al. (1994) found no significant risk elevation in drivers with medically recognized night vision impairment. Nevertheless, it is likely that night vision impairment was underreported in these records (McCloskey et al., 1994). • Sivak et al. (1981) found that the night-time legibility distances for highway signs for drivers 60 years and older was 65–77% the legibility distance for drivers under 25 years old with equal photopic acuity (Olson and Berstein, 1977). • Comparing the vision of individuals between the ages of 5–15 and those aged 75–85, a 50 to 70-fold increase in target screen luminance is required for the older group. There is also a sudden increase in sensitivity to glare at the age of 40 (Wolf, 1960). • Glare resistance is predicted to decrease by 50% every 12 years (Reuben et al., 1988). Under low luminescence conditions, older subjects (who were matched with young subjects on high luminescence visual acuity) read signs at 65–77% of the distance of their younger counterparts (Reuben et al., 1988).

Table 2
Cognitive ability

	Major trends and statistics
Cognitive: response time	• Snyder et al. (1975) report an increase in neck muscle reflex time with age for adult males and females subjected to a sudden lateral load applied to their head. Reflex times for females were 18% longer at age 68 than at age 21, while reflex times were 9% longer in elderly males contrasted with younger males (Schneider and Sprague, 1995). • Data from Stelmach et al. (1987) show that reaction time for arm movement increases with decreased knowledge of impending movement requests (i.e., more uncertainty), and this effect is accentuated by age (Schneider and Sprague, 1995; Stelmach and Nahom, 1992). • Falduto and Baron (1986) and Cerella (1985) found that older adults are significantly slower and take longer to produce movement as the complexity of a task is increased. • A normal reaction time for persons 65 and older range from 300 to 700 ms (Retchin et al., 1988). • With increasing response uncertainty, older adults (60–65) are disproportionately slower than middle aged and young adults (Stelmach and Nahom, 1992; Stelmach et al., 1987; Simon and Pouraghabagher, 1978). • According to Staplin et al. (1986), there is approximately a 2% increase in brake reaction/movement time for every five years, starting with age 15 and ending with the group of individuals 75 years and older.
Cognitive: attention and memory Selective attention	• In a study of individuals between the ages of 65 and 74, only 1.1% of non-institutionalized individuals were estimated to be cognitively impaired, and 17% of those 85 and over were estimated to be cognitively impaired (Kelsey et al., 1989). • Mihal and Barrett (1976) studied the correlation between selective attention and accident rates for two cohorts (25–43 years and 45–64 years). The correlations were not significant for the young group but were higher and significant for the old group (statistics were not given) (Barrett et al., 1977).
Divided attention	• Overall, performance on two simultaneous tasks, requiring motor responses, generally shows age-related decrements (Ponds et al., 1988). • Brouwer et al. (1990) showed that when one of two required motor responses was replaced by an oral response, the age effect was reduced substantially, but it was not eliminated (Sivak, 1995). • Older adults divide their attention less effectively than middle-aged and young adults, who did not differ from each other (Brouwer et al., 1991). • In lane tracking, an age-associated dual-task deficit Brouwer et al. (1991) found (i.e., relative to a single-task performance). Brouwer et al. (1991) interpreted differences in single-task performance among individuals, controlled by means of adaptive tasks, as an impairment of divided attention.
Alzheimer's disease	• The memory of recent events is affected more severely than remote memory in Alzheimer's patients (McKhann et al., 1984). Patients in the early stages have difficulty with shifting, disengaging, or switching attention, yet their ability to engage and focus attention remains relatively in-tact (Parasuraman and Nestor, 1991). • Dementia is associated with increased divided attention costs or dual-task decrement (i.e., the relative decrease in dual-task performance compared with single-task performance) (Baddeley et al., 1986; Nestor et al., 1991a,b; Parasuraman and Nestor, 1986; Tinklenberg et al., 1984).

Table 3
Physical strength and dexterity

	Major trends and statistics
Arthritis	• In a comprehensive survey of elderly drivers, 35% of the study population reported problems with arthritis, and 21% claimed that it was difficult to turn their heads and look to the rear when driving (Yee, 1985). • Arthritis is experienced to some degree by approximately half the population over age 75 (Adams and Collins, 1987; Schneider and Sprague, 1995).
Physical strength	• Several authors have reported strength declines in the elderly, ranging from 0% to 30% per decade, depending on the age groups and muscles studied. This effect becomes more pronounced with advancing age beyond 65 years (Shephard et al., 1991; Bassey and Harries, 1993). • Elderly men have an average dominant hand-grip score of about 38 kg and a non-dominant hand-grip score of 35 kg (Retchin et al., 1988). • Grip strength declines more in women than in men (19% vs. 12%) (Bassey and Harries, 1993; Schneider and Sprague, 1995).
Dexterity	• There is a normal loss in speed of muscle contraction and muscle coordination of 25% between ages 30 and 70 years (Blocker, 1992). • In a study performed by Brouwer et al. (1990), when one of two required motor responses was replaced by an oral response, the age effect was significantly reduced. Nevertheless, it was not eliminated. This result is consistent with the view that motor skills are particularly affected by the aging process (Korteling, 1991).
Joint flexibility	• According to Smith and Sethi (1975), joint flexibility declines by approximately 25% in older adults. • Overall, the elderly have approximately 12% less cervical (neck) flexion, 32% less neck extension, 22% less lateral flexion, and 25% less rotation than younger control groups (Kuhlman, 1993; Snyder et al., 1975). • Normally, muscle strength declines approximately 12–15% between the ages of 30 and 70 (Blocker, 1992).

2.1. Vision

Approximately 90% of the information translated to a driver is visual; consequently, the efficiency of the person's visual perception skills is likely to influence the driver's competence on the road (Simms, 1985). The gradual degradation of eye muscles over time can have a huge impact on an individual's ability to focus on objects at greater distances and under various lighting conditions. Over the course of the aging process, the lens of the eye becomes more opaque and less elastic, which makes it more difficult for the eye to focus (Haigh, 1993). Changes in muscles controlling the lens shape reduce the ability of the eye to focus. Furthermore, as the eye muscles weaken, convergence of the lines of sight for both eyes becomes much less efficient (Haigh, 1993).

With respect to lighting, muscle recession often affects an individuals "near point", which means that retinal images are smaller and increased illumination is required for greater acuity (Haigh, 1993; Pulling et al., 1980). For instance, twice as much light is required at age 40 as compared to age 20; and three times as much is necessary at age 60 (Haigh, 1993). "From the 20s there is a decrease in contrast sensitivity but the main decline begins at around 40 or 50 years of age. The discomfort, and even disability, which arises from harsh excess illumination in the form of glare is more troublesome to those over 40 than the young'' (Haigh, 1993, p. 11). Resistance to glare has been predicted to decrease by roughly 50% every 12 years (Reuben et al., 1988).

In a study on the effect of driver age on night-time legibility of highway signs (Sivak et al., 1981), the distance from which participants in two groups, under 25 years of age and over 61, could accurately identify the orientation of the letter ''E'' was recorded. Researchers found that legibility distances for the older subjects were 65–77% of those of younger subjects who had equally high-luminance visual acuity. This finding implies that older drivers are likely to have less distance and consequently less time to react to the information transmitted on highway signs (Sivak et al., 1981). Based on this study, it could be argued that legibility standards for highway signs should not be based solely on data obtained from young drivers, and that high-luminance acuity tests may have questionable relevance for night-time driving conditions and visual performance.

Finally, useful field of vision (UFOV) is the visual field area over which information can be acquired in a brief glance (Sanders, 1970; Ball and Owsley, 1991). As might be expected, older persons tend to have a smaller UFOV than younger persons (Sekuler and Ball, 1986; Sivak, 1995). UFOV, which is used as a selective attention measure, has been related to accident risk in older drivers (Ball et al., 1990; Owsley et al., 1991). However, Brown et al. (1993) found only a weak correlation ($r = 0.05$) between UFOV and crashes (Sivak, 1995).

Not surprisingly, the typical visual impairments associated with aging play a prominent role in an elderly individual's ability to drive an automobile. Many of these impairments could be lessened through new designs for in-vehicle driving aids. Furthermore, many older individuals are unaware of their visual limitations. Informing older drivers of their visual deficits may help drivers to modestly adapt their driving behavior (Ball and Owsley, 1991) or to purchase adaptive equipment for their vehicles.

2.2. Hearing

Hearing begins to decline between 10 and 19 years of age, with deterioration more pronounced over time (Havlik, 1986). It is difficult to determine when normal hearing deterioration begins because this process is affected by many factors such as exposure to noise throughout life, genetic influence, and diet. By the age of 50, however, there is enough hearing loss on average to create impairment under more demanding listening situations, such as faint sounds, background noise, and multiple sources (Haigh, 1993).

Clearly, hearing impairment can be ameliorated with amplification devices; however, amplification is often characterized by an inability to discriminate or understand speech sounds. McCloskey et al. (1994) found that participants (all 65 or older), who used a hearing aid while driving, showed a modest yet significant elevation in risk of having an injury collision. The mechanism for this elevated risk, however, is uncertain given an absence of a significant increase in risk among those with abnormal hearing tests. ''It is conceivable that a hearing aid worn while driving might produce feedback or other sounds that could distract the driver'' (McCloskey et al., 1994, p. 473). With respect to licensure, both the American and Canadian Medical Associations recommend unrestricted licenses for individuals with a hearing deficit of 40 db or less (Reuben et al., 1988; Canadian Medical Association, 1986; Doege and Engleberg, 1986).

2.3. Cognitive: response time

A consistent finding in aging research is that coordination of motor skills slows with increased age (Salthouse, 1985a). In a comparative study of reaction times among elderly drivers (Retchin et al., 1988), drivers were separated into three categories based upon the amount of driving undertaken: (1) frequent, (2) infrequent, and (3) rarely or never. Researchers found that non-drivers had the longest reaction times, more than twice the average time of frequent drivers. Furthermore, frequent drivers responded more slowly than did young adults (Stelmach and Nahom, 1992). In this study, reaction time was defined as the time it took to depress the brake pedal after a light turned from green to red. It is important to note, nevertheless, that simple reaction times alone do not relate to driving performance (Odenheimer et al., 1994). Table 2 summarizes the major trends and statistics related to cognitive response times.

2.4. Cognitive: working memory and attention

Many studies have shown that elderly individuals have more difficulty doing two things at once than do younger people. For instance, elderly individuals have trouble driving, reading a document and typing it, and reading and listening to the radio (Salthouse, 1990; Haigh 1993). In driving performance, visual and attention tasks are important for correct positioning of a vehicle, and selective attention is important for appropriate action in complex traffic situations (Odenheimer et al., 1994; Brouwer et al., 1990).

Divided attention efficiency is known to decline with age (McDowd, 1986; Salthouse, 1985b), particularly with respect to complex tasks (McDowd and Craik, 1988). Older adults seem to have more difficulty ignoring irrelevant information (Rabbit, 1965). This deficit becomes evident for tasks involving memory (Kausler and Klein, 1978), problem-solving (Hoyer et al., 1979), or visual-search (Salthouse, 1991).

Alzheimer's is a particularly important concern for aging drivers. Alzheimer's is estimated to affect between 1.5 and 2.5 million people in the United States (Office of Technological Assessment, 1988). It is estimated that most Alzheimer's patients continue to drive for as long as four years following their initial diagnosis (Friedland et al., 1988). This becomes particularly relevant since clinical reports suggest that even mildly demented persons have trouble concentrating on tasks and maintaining attention (Lezak, 1983).

2.5. Physical strength and dexterity

Physical impairments, such as strength and flexibility, can also have an impact on the ability to drive or ride comfortably in a vehicle. For example, joint flexibility is especially important for driving tasks such as mirror scanning and head turning to observe blind spots (Yee, 1985). As might be expected, the aging process is accompanied by a loss in muscle mass and a reduction in muscle cells, connective tissue, and muscle tissue fluids. Normally, muscle strength declines approximately 12–15% between the ages of 30 and 70 (Blocker, 1992). Various authors have reported declines in elderly strength of between 0% and 30% per decade, depending on the age groups and muscles studied, with the effect becoming more pronounced with advancing age (Shephard et al., 1991; Bassey and Harries, 1993).

In addition, to muscle loss, arthritis can impact driving ability. According to Murray-Leslie (1991), experience with arthritic drivers suggests that chronic joint pain rather than a stiff, weak, or deformed joint is the biggest obstacle to driving. Not surprisingly, climbing in and out of a vehicle is particularly difficult for elderly individuals with arthritis.

Another aspect related to arthritis is hand functioning. Hand functioning affects how individuals hold and use tools and how they manipulate controls and products related to vehicles. "With age there is a decrease in hand strength, dexterity, precision, coordination, joint mobility and sensitivity. Older people may also suffer from diseases such as arthritis which can result in swollen and painful hands" (Haigh, 1993, p. 12). In a general study of adult hand function, Shiffman (1992) found that task performance time tended to remain stable until age 65 years, after which it diminished slowly. After age 75, differences in performance become much more apparent (Schneider and Sprague, 1995).

Furthermore, there is a decrease in grip strength and endurance with age, specifically the amount of force that can be exerted when clamping something in the hand and the length of time this concerted pressure can be maintained. Haigh (1993) found a 16% decline in grip strength between the ages of 20 and 60, a 40% decline in grip strength from the ages of 30 to 80 when measured cross-sectionally, and a 60% decline between the ages of 30 and 80 when measured longitudinally. Hence, an individual of age 65 years or more can achieve only about 75% of their earlier capacity in strength and endurance. If muscle strength also deteriorates, there may be a reduction in the accuracy of movement as well (Haigh, 1993).

In addition to grip reduction, there is a corresponding reduction in finger and thumb strength, for instance, when a finger or thumb is used to depress a button. Researchers estimate a decrease between approximately 12% and 19% from age 20 to age 60 (Schneider and Sprague 1995). Clearly, a decline in hand functioning may affect an individual's ability to operate a vehicle and should be considered when designing vehicle controls. Table 3 summarizes the major trends and statistics related to physical strength and dexterity.

2.6. Compensating factors

Several studies have shown that perceptual and psychological (behavioral) mechanisms exist to compensate for specific types of functional loss (Loomis et al., 1998; Klatzky et al., 1990; Manton, 1989). Loomis et al. (1998) conducted three experiments to investigate the auditory and visual distance perception of over 40 research subjects. Participants received visual and auditory cues that directed them to walk toward a target location. "Under full-cue conditions, the average observer performed quite well; however, under reduced-cue (e.g., impaired) conditions, the average observer walked beyond the two nearer targets (1.5 and 3.1 m) and walked well short of the far target (6.0 m)" (Loomis et al., 1998, p. 977). Visually based motor coordination was less variable than auditory-based coordination under reduced-cue conditions. To summarize, motor coordination accuracy was reduced under impaired conditions and at greater distances. Nevertheless, some compensation is likely to occur for both visual and auditory perceptual functions.

In a related study, Klatzky et al. (1990) examined navigation ability in the absence of sight. Researchers concluded that navigational abilities (i.e., cognitive motor coordination performance) were quite accurate for simple pathways, in the absence of vision, particularly for sighted or formerly sighted individuals. However, this was not the case for more complex pathways. From this experiment, it might be inferred that compensating mechanisms were countering the effects of blindness or greatly reduced vision for simple pathways. Manton (1989) argues that there is a much greater potential for rehabilitation at advanced ages than previously expected. Based upon his review of the literature, Manton indicates that acceptance of age-related functional losses can negatively impact actual abilities (i.e., a self-fulfilling prophecy) and recommends that a more active approach to preserving functional abilities be adopted at later ages by reinforcing a positive self-image in the elderly.

3. Human factors and basic vehicle design adaptations

According to Carp (1988), technological adaptations can ameliorate some age-related impairments. For instance, sign readability and signal timing are design elements that can greatly affect an individual's ability to travel safely, and for which simple technological adaptations can prove useful. In particular, products designed for an older population must increasingly meet the needs of older females (Pirkl, 1994). The increasing number of older women "amplifies the growing needs for anthropometric and behavior research among this group. Designers and human factors specialists need additional data for the older population in general and women in particular" (Pirkl, 1994, p. 17). As the number and economic status of older consumers increases, the collective strength of this growing population may convince many companies that products and environments that compensate for sensory and physical impairments have a market advantage (Thompson, 1995; Pirkl, 1994).

In this section, we describe several kinds of possible vehicle design adaptations, including: seating; seat and doorway dimensions; handles, knobs, and steering wheels; anti-glare adaptations, mechanical driving controls, and seat belts, that can serve the older population. The design standards for these adaptations can be ascertained using the research presented in the previous section. Many changes could be made to a standard vehicle with little effort on the part of automobile manufacturers. For instance, very simple transgenerational adaptations might include the use of aromatherapies, which could be released inside an automobile to stimulate and awaken tired drivers. Other adaptations will require a more radical approach to developing new standards for vehicle design, such as doorway and headlight height alterations. As might be expected, many of the adaptations we explore may be costly. Design changes that are made on all vehicles (e.g., knob design) would benefit from economies of scale, while other, more customized designs would remain costly. Although costs play a key role in market demand, they are not emphasized in our evaluation. The recommendations we identify are included in Table 4.

3.1. Seating

Vehicle seating should be relatively hard and flat, making it easy to sit down on the edge of a seat and then move into a comfortable position. Consequently, a seat surface should not have too much friction, which makes it more difficult for passengers to swivel when getting into and out of an automobile. The seat position should also be easy to adjust by all passengers (Petzall, 1995).

Vehicles with a single door on each side provide the easiest access due to a wide door aperture. The maxima and minima for door aperture and seat dimensions, which would be acceptable to

Table 4
Seat and doorway dimensions

Doorway width	A minimum of 800 mm and for comfort reasons at least 900 mm.
Seat position	Space between the seat front right cover and the front door-post should be a minimum of 300 mm, and for comfort reasons at least 350 mm. Distance between the backrest of the seat and the front door-post should be a minimum of 840 mm and for comfort reasons up to 930 mm. The seat should be adjustable to a position where the upper portion of the seat backrest is placed at the same horizontal position as the back door-post.
Door-sill height	A maximum of 90 mm above the floor and for comfort reasons less than 50 mm.
Doorway height	A minimum of 1330 mm and for comfort reasons at least 1380 mm above the ground.
Door angle	Angle to which the door opens, approximately 70 mm (for ambulant disabled persons); 70 mm for wheelchair users; and 90 mm (for wheelchair users with an assistant).

90% of the disabled population, have been determined by the Institute of Consumer Ergonomics (Murray-Leslie, 1991). Increased front seat retractability or adapted vehicle seats, which slide back and swivel outward, can provide great assistance to the physically impaired. Providing better seating designs and relocating primary vehicle controls closer to drivers will also aid mature adults, who have experienced a decrease in intervertebral disk spacing in the spine and possess a characteristic round back (Thompson, 1995).

3.2. Seat and doorway dimensions

In an experimental study Petzall (1995) asked 17 elderly and disabled participants to enter and exit a mock-up vehicle that had a doorway whose width and height could be altered. The results helped to define the minimum vehicle doorway dimensions required to comfortably accommodate individuals with a mobility impairment, enhancing comfort and safety during entry–exit operations. Dimensions are provided in Table 4.

3.3. Seat belts

According to Murray-Leslie (1991), for most individuals the arthritic discomfort associated with operating and wearing seat belts can be overcome or ameliorated. Adjusting the belt anchorage points and system slack will accomplish this. Nevertheless, it is important to realize that such alterations could affect the safe functioning of the belt and should only be undertaken by a specialist.

3.4. Handles, knobs, and steering wheels

Handles, knobs, and steering wheels can be adapted to meet the hand functioning needs of the elderly (e.g., arthritis and reduced strength). The effort and torque requirements for control knobs and levers should reflect the gradual decline in physical strength and dexterity over time (Thompson, 1995). Petzall (1995) recommends that suitable handles be mounted to accommodate the needs of individual drivers. Suggested locations include the dashboard, the upper part of the front door-post, the roof inside the upper part of the door frame, and on the door just beneath the window. Strategically placed handles can aid passengers when getting into and out of a car.

As noted earlier, arthritis research suggests that joint pain rather than stiff and weak or deformed joints present the biggest obstacle to driving. This pain may be related to joint movement or pressure from maintaining a limb in a particular posture. To minimize this pain, the position of the vehicle controls and seating should be optimally placed to reduce the forces and pressures required for operating controls. Additionally, control maneuvers, such as gear changing, should be eliminated (Murray-Leslie, 1991).

Based on a review of ergonomic field research (Haigh, 1993), the following guidelines were suggested to help automobile drivers and passengers with declining hand function, especially those caused by arthritis:

- enlarged vehicle knobs, handles, and steering wheels;
- knob shapes should be easy to hold, so that it fits the hand;
- texture should be easy to grip and hold;
- stop and start should be located apart from one another; and
- facilitate single-handed tasks if possible.

3.5. Anti-glare adaptations

Glare reducing vehicle modifications that should help elderly drivers include non-glare panels and day/night rearview and side mirrors. Other visibility enhancements may be achieved through improved headlight designs, for instance mid-beam headlights that increase distance visibility but not the glare from oncoming cars (Shinar and Schieber, 1991). Furthermore, a headlight washing and wiping system could be added to ensure cleanliness and enhance luminance (Mortimer and Fell, 1989). Haigh (1993) suggested the following design guidelines to improve the visibility of vehicle control panels and dials (based on Pirkl and Babic, 1988):

- ensure adequate light level on text and controls;
- select appropriate color, size, and chromatic intensity for type symbols;
- isolate priority information from background clutter and glare;
- eliminate irrelevant information and decoration;
- use appropriate type size and weight and letter, word, and line spacing;
- maximize contrast between type and background;
- use non-reflective surfaces;
- use contrasting colors; and
- use blue-violet green combinations with care.

3.6. Mechanical driving controls

Adaptive driving controls, such as mechanical hand controls or electromechanical contact switches, now allow even the most severely impaired to operate a vehicle. However, these mechanical functions are usually directed toward primary controls only, such as steering, braking, and accelerating, which limits the ability of drivers to operate secondary controls such as the horn, turn signals, ignition, and headlights, etc. (Quintin et al., 1991).

The most significant progress to aid disabled drivers has been made with vehicle control adaptations, which can be effective, simple, and inexpensive. These include the use of simple extension bars to gear levers and lever release mechanisms for hand braking. "Other items such as electrically adjusted car seats, infra-red systems for the operation of vehicle controls, and vacuum assisted braking usually cost well under [$2,000]" (Murray-Leslie, 1991, p. 55). Occasionally, when arthritis is severe and accompanied by limb deformity and shortening or neurological weakness, more expensive and specialized vehicle controls may be necessary (Murray-Leslie, 1991).

3.7. Auditory information systems

To enhance, the auditory impairments of the elderly and disabled populations, Haigh (1993) has suggested the following audio design guidelines to support these needs (based upon Pirkl and Babic, 1988):

- Provide a control for sound to ensure that the loudness level can accommodate all users regardless of sensitivity.
- When communication impact is critical, relate the sound volume to the cue urgency and provide both visual and audio cueing.
- Minimize the ambient sound produced by the product or environment so that confusing audio signals are eliminated.
- Avoid irrelevant information: if older people have to process a lot of information they are likely to take longer to perform a task.
- Use lower frequencies for alarms and urgent messages.

In the research on advanced cueing by Staplin and Fisk (1991), 103 young (average age of 37) and older drivers were tested in intersection approach simulations with and without cueing. The results indicate that decision rule cueing provided by an advanced and redundant stream of sign elements, will improve the accuracy and latency of both younger and older drivers' decisions.

4. Human factors and intelligent transport technologies and support services

Advanced technologies can greatly enhance or extend private vehicle mobility for the elderly. Enhancements might include specialized driving aids, such as auditory information systems, visual enhancement devices, and smart cards; and in-vehicle information and support systems, such as planning and en-route information systems, vehicle operation and maintenance devices, emergency aid networks, and safety enhancements. As with any discussion of intelligent transportation systems (ITS) technologies and the physically impaired, it is important to recognize that many of these technologies may not be readily accepted at first due to an age-related aversion to new technologies. For subsequent generations, this will be less of an issue because they will become familiar with intelligent technologies at an earlier age. It is also worth noting that many ITS adaptations may initially be costly to implement. Nevertheless, it is plausible that technology costs will decline over time and many basic features (e.g., in-vehicle navigation) will become integral to vehicle design in the near future.

4.1. Visual enhancement devices

A comprehensive study of elderly drivers conducted by Yee (1985) indicated that 35% of those surveyed reported problems with arthritis, and 20% claimed it was difficult for them to turn their heads to look behind when driving. A user-centered approach to ITS deployment for this impairment might include such features as rear proximity warning systems to prevent risky entrance into the path of another vehicle (Owens et al., 1993) or a laser/radar system devised to sound an audible warning when a motorist initiates a risky lane-change. Infrared (IR) video systems provide another possible technological means for improving driving conditions by illuminating dark environments. These systems are similar to the night vision systems used by the military. From a user-centered perspective, this technology offers an unprecedented possibility to enhance visual access in the night traffic environment.

Innovative vehicle designs can also consider novel possibilities such as better display positioning and the use of heads-up displays. These modifications would simplify an individual's visual search. This feature would be extremely useful to individuals with cognitive (e.g., response time limitations) and visual impairments (Shinar and Schieber, 1991).

4.2. Smart cards

Smart cards are an advanced technology that is particularly suitable for a variety of applications, including automated payment. Smart cards are approximately the same size as a conventional credit card. They contain both microprocessor and memory elements that allow them to perform calculations and manipulate data independent of smart card readers. Individuals with cognitive, mobility, or agility impairments could smart cards to recall seating, mirror, or steering adjustments. People with agility impairments could also benefit from smart cards use by avoiding money handling at tollbooths and parking lots. At present, smart cards that can read and write data links in a contactless manner are already available. They can provide a robust and secure method of data processing and information portability.

4.3. In-vehicle information and support systems

There are several in-vehicle information and support systems that could be developed to address declines in perceptual, cognitive, and physical performance (Flyte, 1995):

- *Collision risk determination systems:* support a driver with recommendations or warnings for a particular traffic scenario based on on-board real-time risk assessment intelligence.
- *Dynamic route navigation systems*: provide a driver with explicit routine information for specified trips. Similarly, Sixsmith and Sixsmith (1993) recommend a *radio data system*, a voice-activated radio that could provide elderly drivers with local road and weather condition broadcasts on request.
- *Vehicle condition monitoring*: provide a driver with information on vehicle maintenance, including brake wear, washer fluid level, etc.

- *Driver condition monitoring*: provide a driver with information to help maintain adequate driving performance. Such systems would monitor fluctuations in key driving factors associated with the effects of medications, sleepiness, and cognitive underload and overload.
- *Road and route information systems*: enable a driver to plan her route, accounting for road type and preferences for the shortest, fastest and most scenic routes, etc.
- *Parking guidance systems*: provide information about the location and availability of parking spaces, which can assist all drivers (Kaszniak, 1991).
- *Portable mobile data terminals*: provide a driver or passenger with information regarding the status of traffic and road conditions.

4.4. Operation and maintenance systems

Before traveling, drivers often require vehicle operation and maintenance information, such as brake, tire, engine, and fluid conditions. In addition, emergency and repair information services prior to long trips would be particularly useful to the elderly. Such information needs could be met by a combination of ITS technologies, such as vehicle diagnostic systems, in-vehicle communications, vehicle location devices, and roadside and emergency facility databases.

Furthermore, a national workshop explored the need for a national emergency aid network developed to assist individuals driving adapted vehicles (TRB, 1991). This service would facilitate the rescue of stranded individuals and guarantee repair services for specialized vehicles, which typical automobile repair providers do no offer. This emergency network would employ automatic vehicle location, advanced traveler information systems, and advanced traveler management systems technologies.

4.5. Safety systems

For individuals with visual or cognitive impairments, visibility and recognition is often difficult, e.g., the traffic and street sign restrictions listed on a parking sign cannot be read from a distance. In-vehicle signage could provide a potential solution to many such problems. This same group of individuals could also benefit from denial systems. Denial systems prevent individuals from driving under certain conditions, e.g., poor lighting for persons with visual impairments (Guthrie and Phillips, 1994).

4.6. Mobility support services

Mobility support service centers could provide expert consultation and assessment of physical and cognitive impairments pertinent to auto-related mobility. Such an evaluation might aid a driver in making important travel behavior adjustments (e.g., driving only during the day). Moreover, support centers might include expert technological design services, which provide recommendations and advice for linking impairments to vehicle adaptations and intelligent systems (e.g., visual enhancement devices). In the near future, the need may also exist for more sophisticated driver training, especially for the elderly. Ready access to good quality and unbiased advice based on sound assessment of driving needs remains a major problem for elderly and disabled individuals. In the United Kingdom (UK), however, there is a network of driving assessment centers where individuals can obtain a practical assessment of driving ability and recommendations for driving adjustments can be made (Murray-Leslie, 1991).

In the future, such centers could also provide expert technological design services for linking impairments to vehicle adaptations and intelligent systems. Countries dependent on private vehicles for mobility, such as the United States, should consider supporting mobility service centers for the cognitively and physically disabled similar to those in the UK. These centers could be operated initially through public–private partnerships. Health providers and automobile manufacturers may be interested in jointly exploring such a venture.

Countermeasures, such as physical therapy, could be offered through a mobility service center to help improve and maintain the skills of elderly and disabled drivers. Not surprisingly, rehabilitation strategies have been shown to help an individual overcome a loss either directly or by developing other problem-solving skills (Fisk, 1993). Recently, Ashman et al. (1994) conducted a two-year study of the problems of 105 older drivers. The purpose of this research was to develop and evaluate countermeasures for improving older driver safety. During the first year, the problems of older drivers were examined and countermeasures were identified, including: (1) physical therapy, (2) perceptual therapy, (3) driver education, and (4) infrastructure design. Participant driving performance was measured using the driver performance measurement (DPM), developed at Michigan State University. Each subject was tested before and after each countermeasure was employed. In the second year, the effects of these driver countermeasures were evaluated. The results indicated that all the countermeasures improved the driving performance of older adults.

Ashman et al. observed that the study's rehabilitation countermeasures provided a 7.9% improvement in driving performance (based on the change in DPM score) for each measure. Further, driver education combined with physical or visual therapy tended to improve driving performance. Nevertheless, none of the increases were found to be statistically significant ($P < 0.02$). Finally, Ashman et al. found that infrastructure adaptations would be the most cost-effective on high-volume roadways, and other countermeasures (e.g., physical and visual therapy) would be the most cost-effective on low-volume roadways.

This study also included an evaluation of three nationally prominent driver education programs: (1) the National Safety Council's *Coaching the Mature Driver*, (2) the American Association of Retired Person's *55 Alive/Mature Driving*, and (3) the American Automobile Association's (AAA's) *Safe Driving for Mature Operators*. Ashman et al. concluded that all three programs provide adequate.

4.7. Testing and licensing

Although the licensing of elderly drivers is a hotly debated issue in many states, it could be a critical tool for regulating future driving rights. Recently, Levy et al. (1995) found that states with license renewal policies, mandating vision tests for all drivers, were associated with fewer fatal crashes among the elderly. There is also evidence that driving knowledge tests have been associated with fewer fatal crashes involving older drivers. In states that do not impose testing for license renewal, mobility centers could provide a valuable consultation and assessment service, particularly for elderly drivers who may be unaware of their physical and cognitive impairments.

Johnson and Keltner (1983) found that a majority of their research subjects, who had been diagnosed with abnormal visual fields (57.6%), were unaware of any visual difficulties. Bengtsson and Krakau (1979) found similar results in an automated visual field test study. In this experiment, 48% of the subjects diagnosed with a visual field loss were previously unaware of this problem. In summary, these results suggest that automated visual field tests for driver screening can provide a valuable assessment tool.

At present, the availability of instruments for assessing dynamic visual perception skills is still quite limited. The Doron Corporation offers a Precision Systems Driver Analyzer; this tool can provide accurate and dynamic measurements for evaluating a driver's perceptual skills, reaction time, and threat recognition abilities. The visual evaluation aspects of this system can be especially useful to clients in evaluating their visual scanning and attention abilities (Pirkl, 1994). Visual evaluation tools, such as the driver analyzer, could be used at mobility service centers to evaluate the driving abilities of the elderly. The results of these assessments could be used to link driver impairments to vehicle adaptations and intelligent system devices.

5. Conclusion

Increasingly, the topic of elderly mobility surfaces as a key determinant in the well-being of expanding aging population. Recently, several elderly related lifestyle issues have attracted considerable attention, including: health-related perceptions, elderly housing, and the combined decline in both mobility and well-being in the aged. Indeed several studies indicate that lower self-esteem and increased feelings of uselessness, unhappiness, and depression accompany reduced mobility in the elderly. Although a causation effect between declines in mobility and well-being is difficult to ascertain, this coincidence warrants further investigation (Carp, 1988).

While many limitations associated with aging may not be apparent in day-to-day activities, the limitations are likely to be more evident in the presence of a complicating factor, such as an unfamiliar technology. Consequently, many elderly individuals may have a negative attitude toward the incorporation of ITS technologies into their driving tasks. Because a large percentage of the driving population is over age 50, it is critical that ITS designers try to match the human–machine control systems they develop to the capabilities and needs of these older drivers (Haigh, 1993). At present, little research has been conducted on user acceptance of new mobility technologies for the elderly.

This paper begins the dialogue among transportation, design, and medical experts by describing a range of physical and cognitive impairments related to driving and how such disabling effects can be reduced through a wide-range of design modifications (e.g., seat and door standards). We have advocated a new design approach that develops vehicle products and services to aid the elderly, yet is flexible enough to serve the mobility needs of many users, ranging from young adults to the oldest of the elderly. This approach would encourage wide spread adoption of many products and services that support the changing physical and cognitive needs of individuals throughout a lifetime. Consequently, many of these products would be less specialized for a particular impairment, more affordable, and widely available to individuals from a range of socio-economic backgrounds.

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