Driving Behavior and the Aging Society: a Framework for Microsimulation Approach

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Abstract

In Japan, the rapidly aging society requires a special perspective in traffic engineering to address the occurrence of severe traffic accidents involving elderly drivers. The route to incorporate the behavior of elderly drivers into traffic analysis, and to assess the benefits of emerging technologies such as autonomous vehicles to this growing social group, must contemplate the proper representation of elderly drivers´ driving behavior in analysis tools such as microsimulation. This paper introduces exploratory research to identify the attributes required to accomplish the representation of elderly drivers in microsimulation models.

Keywords: Elderly driver; Calibration; Microsimulation; Safety

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1. Introduction

The participation of elderly drivers in traffic accidents is increasing in several countries (Tai et al., 2019). In the United States, Lyman et al. (2002) estimated that, in the period 1999 and 2030, for all age groups there will be an 39% increase in the number of drivers involved in fatal crashes, while the increase for the group aged 65 and older will be 155%, accounting for 54% of the total projected increase in fatal crashes.

In Japan, 55.4% of all traffic fatalities in 2019 involved people aged 65 or older and accidents involving pedestrians are one of the most common types of traffic fatalities reaching 36.5% of total. Moreover, stop-sign violations featured in 16.7% of all crashes resulting from traffic violations (Japan, 2019). Elderly drivers are particularly prone to inadvertently ignoring stop signs at unsignalized intersections (Manning at al., 2019; Bao and Boyle, 2008).

The most frequent occurrences of traffic crashes involving elderly include lateral collision due to changing lanes, late brake down crashes, sudden change in acceleration or deceleration, and mistakenly using the throttle paddle as a brake (Segal et al., 2019).

Rural areas and low-density urban sprawls tend to be poorly served by public transportation due to the continuous optimization of public transportation supply and irregular demand, since the trend of younger population moving to denser areas have been observed worldwide for some decades. In this scenario, elderly populations rely on individual use of private cars to ensure mobility and access to services such as medical consultations and shopping activities.

In the context of a super-aging society, it becomes a urgent task to reduce and prevent traffic accidents involving elderly drivers (Oshima, 2017).

In Japan, the driving ability of elderly drivers is assessed through National Police Agency driver aptitude tests administered during elderly driver workshops conducted at the time of driver license renewal. These tests include written tests of driving behavior, decision performance and temperament, and computerized tests of factors such as reaction time, reaction consistency and steering. However, these tests do not incorporate actual driving situations, offering an incomplete assessment of visual, cognitive and decision performance while driving (NAKANO et al., 2008). As a result, elderly drivers are at a remarkably high risk of traffic accidents largely due to their higher frequency of failures, which could be often resulted from the neurological and physical impairments because of the aging effects (DUC-NGHIEM et al., 2016). Already, in Japan, the proportion of traffic accidents caused by elderly drivers increased year-by-year, and the mortality was highest in the those aged above 75 years (Nishiuchi et al., 2021). As for non-fatal accidents, the progressive increase in occurrence can be observed since the driver reach mid-50 age group, and drivers who had no accident experience in the previous three years began to exhibit higher relative accident ratios after the age of 70 (Nishida, 2015). Moreover, Inagaki et al. (2019) analyzed the driving behavior data collected using driving recorders in everyday life situations of elderly drivers in Japan, concluding that abrupt deceleration and safety confirmation behaviors differs considerably according to individuals. Matsumoto et al. (2008) explored in further detail the causes and processes of accidents involving elderly drivers, concluding that short-sighted decisions, lack of appropriate attention, and difficulty processing multiple pieces of information are decisive factors contributing to traffic accidents caused by elderly drivers, identifying intersection-based measures that encourage improved safety behavior in elderly drivers.

Research on autonomous cars has been actively conducted worldwide, where one of the explored objectives considers that the technology is expected to decrease the number of traffic accidents involving elderly drivers. However, realization and diffusion of autonomous cars still needs considerable time due to the need for change in road use regulation, high cost of vehicles, and need for technology. In the meantime, a lack of driving the car as a mode of transportation can diminish the quality of life of the elderly and increase the possibility of them developing dementia (Chihiru at al., 2016).

2. Literature review

2.1. Elderly driving behavior and safety

Safety issues related to elderly drivers have been studied from different perspectives. Among them, this study reviews previous research on the correlation between safety issues and the cognitive degradation of elderly drivers, as well as the development of technological features to compensate for such degradation.

According to Mackenbach and van der Maas (2008), the quality of our senses, and consequently our ability to orient ourselves in the world, will deteriorate as we age. Our visual and auditory senses will decline especially faster, starting around age 45. Such decline can be compensated by eye-sight correction and hearing aids.

Major health-related factors in traffic accident risk in the elderly include declining physical function (e.g., eyesight, neurological and cognitive function) (Klein, 1991, Mori and Mizohata, 1995, Wong, 1987) and the presence of medical illnesses (e.g., heart conditions, diabetes, cataracts, arthritis etc.) that cause physical limitations (Karceski & Gold, 2011). Most studies investigating the relationships between health status and car accidents among older individuals have focused on older drivers' health conditions. Additionally, the variability of older peoples' lifestyles in various countries convincingly reflects the fact that the determinants of traffic accidents may differ across social and environmental contexts (Hong et al., 2015).

Marottoli et al. (1994) studied the correlation between the presence of healthy issue factors and the occurrence of adverse driving events in multivariate analysis with adjustment for driving frequency and housing type, considering factors as poor design copy, fewer blocks walked and foot abnormalities, which serve as proxy for underlying health conditions. The adverse driving events included crashes, moving violations, and being stopped by police. Using a baseline where 6% of the drivers experienced adverse driving events, results showed that in the presence of 1 factor, adverse driving events increased to 12%. When considering 2 and 3 simultaneous factors, the occurrence of adverse driving events increased to 26% and 47% respectively. Similar results were obtained regarding the ability of the driver in maintaining the vehicle position in a closed course (Odenheimer et al., 1994); the driving performance with simulated visual impairment (even though legal requirements were satisfied (Wood & Troutbeck, 1995).

The driving characteristics of elderly drivers were also addressed. Adults were found to initiate and execute movements more slowly and with less precision as they age, which may contribute to the decline of their driving skill

(Stelmach & Nahom, 1992). Nishida (1999) examined the driving characteristics of elderly and young drivers who were following another vehicle. The analysis of vehicle and driver behavior data such as vehicle speed, space headway, operation of brake/accelerator pedals, and road traffic conditions concluded that the average reaction time of the elderly drivers is longer than that of the younger drivers; the average space headway of the elderly drivers is almost the same as the younger drivers; the average speed of the elderly drivers is slower than that of the younger drivers; and average time headway of the elderly drivers is longer than that of the younger drivers. In another study, older and younger drivers´ propensities to be involved in accidents when performing specific maneuvers. The findings show that older drivers are more likely than younger drivers to be involved in accidents in left turn against incoming traffic, gap acceptance for crossing high speed roads, and lane changes in high-speed roads. Additionally, the study found that older male drivers are safer than older female drivers in left-turn crashes and gap acceptance–related crashes and having a passenger beside the older drivers makes for a safer driving environment (Chandraratna & Stamatiadis, 2003). The issue of unsafe lane change and traffic merging in high-speed roads by elderly drivers was also addressed from the point of view of lack of/ineffective checking of blind spots by older drivers compared to younger drivers (de Waard et al., 2009).

Among the factors affecting the severity of motorized vehicle crashes involving elderly drivers, failing to yield right-of-way, disobeying traffic signs, and unsafe overtaking maneuvers have been shown to have a high correlation with fatal injure in crashes among elderly drivers (Zhang et al., 2000).

Speed control was also identified as a contributing factor to accidents involving elderly drivers. Broberg & Dukic Willstrand (2014) evaluated road driving skills using expert assessment, together with visual and cognitive tests and subjective driving assessment by in-depth interviews with drivers aged 70 years or older. Results showed that inability in adapting speed to the situation and driving too fast, especially on straight roads in the city area is one concern. During the on-road assessment, 90% of the participants were driving too fast on one or more occasions. Seeking the attention of other road users, particularly on the left and right was another issue identified. The latter occurred mostly in intersection and roundabout scenarios.

Infrastructure elements were also identified as contributing factors. Amiri et al. (2020) indicated that the light condition has been the most significant parameter in evaluating the level of severity associated with fixed object crashes among elderly drivers, which is followed by the existence of the right and left shoulders.

The decision by the elderly drivers to drive or not drive is related to social factors. Persson (1993) showed that most of the elderly in the studied group stopped driving when a threshold was reached after an accumulation of compensatory behaviors. Few stopped because of their doctor's advice, although all felt a physician was in the best position to evaluate driving, and family involvement received limited consideration. Another study on a large population-based health survey carried in Canada shows that elderly people who drive are more likely to be male, to be married and to report no more than one chronic disease. Elderly people who do not drive are more likely to live in larger households and to report two or more chronic diseases. Although many of these factors are clearly related to one another, they exert independent associations with whether people drive after other factors have been controlled. Drivers and non-drivers were shown to have similar frequency of contact with family and friends after other variables have been considered (Chipman et al., 1998).

The reduction in driving frequency by elderly drivers was shown to be related to physical impairment, as it was found that there is no significant correlation between driving frequency and age, results of formal cognitive testing, or stroke history, however, significant correlations were identified between driving frequency and differences in grip strength, reaction time, static visual acuity, dynamic visual acuity, and peripheral vision, indicating that subtle motor and visual deficits may play an important role in the reduction of driving frequency by elderly drivers (Retchin et al., 1988).

A large-scale survey addressed the typification of driving events in people aged 50 and over. This study applied a 24-item driving behavior questionnaire to a large sample of older drivers. The distinction between violations, errors and lapses reported in Reason et al. (1990) and replicated by Parker et al., 1995a, Parker et al., 1995b was broadly supported, providing further support for the conceptual distinction between these three types of bad driving. (Parker et al., 2000).

Albert et al. (2018) addressed the challenge of safe driving among elderly drivers, concluding that integrated and applicable procedure of advanced technologies and policy steps to support elderly drivers and their close circle to cope with the complexity of elderly driving may serve as a desired countermeasure.

The relationship between crash occurrence and the factors which potentially contribute to crashes were examined to better understand their influence on elderly drivers and to compare the performance of elderly to younger drivers. To understand the relationship between age and likelihood of causing an injury crash, drivers were grouped into six age categories, where logistic regression on a dataset, which included records irrespective of whether they were linked to hospital records, concluding that younger drivers (younger than 20 years old) are most likely to be at fault in a crash, indicating other vulnerable age groups beyond elderly drivers (Sagar et al., 2020).

The benefits of electronic guidance systems were evaluated against the potential information overload to elderly drivers in a study by Pauzie and Marin-Lamellet (1989), when the authors addressed the behavioral and visual strategies of elderly and young drivers considering simultaneously the drivers gaze movements and field of view. The methodology consisted in having subject drivers to travel under guidance of electronic equipment while driving performance was evaluated based on travel time and number of navigational errors. The authors concluded that aging drivers modified their visual strategies under guidance situations, so that duration and frequency of glances towards navigational system were higher for elderly in comparison to young adults, inducing a noticeable decrease in the time spent looking at the road.

Hosokawa et al. (2008) explored the driving behavior parameters for right turns using a driving simulator. Evaluation was performed using the yaw direction head variation (HeadYawFrequency), where the number of times to check left and right was also evaluated as one time when the head moved more than 10 degrees to the left and right before starting to turn right. The author also indexed the number of peak brakes, pedal strokes, and the operation timing of the running speed indicator. As a result, it was found that a high correlation can be derived by using three indicators: the number of left and right confirmations, average speed, and blinker operation timing.

Mulder and Abbink (2008) addressed curve negotiation, which is another specific situation in which deterioration of sight and hearing affect elderly drivers. That study evaluated the use of haptic guidance system for curve negotiation. Haptic technology, also known as kinaesthetic communication, refers to technologies that can create an experience of touch by applying forces, vibrations, or motions to the user. The study reported positive results in increasing curve negotiation performance with less control activity. As an unexpected effect, the use of haptic guidance system led to a relatively large increase in steering forces. The analysis presented in that study looked at the ability of the driver to keep the lateral position on the lane, which is a common metric for driving behavior evaluations (Griffiths and Gillespie (2004) and Forsyth and MacLean (2006). Moreover, the ability of driver to follow the curvature of the track was also determined as a measure of efficiency of the driver. Such evaluation was based on the time-to-lane crossing (TLC) as described by Mammar et al. (2006).

An evaluation of simulated augmented reality windshield display as a cognitive mapping aid for elderly drivers shows that it results in a significant reduction in navigation errors and distraction-related measures compared to a typical in-car navigation display for elder drivers. These results help us understand how context-sensitive information and a simulated augmented reality representation can be combined to minimize the cognitive load in translating between virtual/information spaces and the real world, reducing the impact of cognitive degradation (Kim & Dey, 2009).

In a broader examination, a review of in-vehicle systems suggests that providing feedback and support to elderly drivers has the potential to enhance their safety on the road and benefit the transport network as a whole. Driver feedback offers information on elderly drivers' driving performance and helps them be aware of the misjudgments or driving errors being made. Driver support provides elderly drivers with timely and constructive advice, alerts, warnings, or even active interventions which take over the activity from the driver to avoid accidents or reduce the seriousness of the accidents. Driver feedback and support can be delivered either in-vehicle using head-up displays or off-vehicle using a home computer or other personal mobile devices (Guo et al., 2010).

Akagi and Raksincharoensak (2015) proposed a driving safety evaluation method to address the decrease in driving abilities of elderly drivers. In order to assess the impact of age in reaction, recognition, and judgement time, that study used a risk potential model to evaluate the driving behavior in terms of speed and cruise control around the risk factors. Experimental data was collected for elderly drivers, as well as for general and normative drivers to serve as control group. The study showed that risk potential parameters can successfully be used to represent the features of elderly driver behavior, specially through the change in minimum speed position before an intersection, therefore, impacting the required deceleration.

Internationally, various studies address the need for assistive driving technology targeting elderly drivers. Huan, K. et al. (2018) argues that driving assistive technology benefits are represented by the increasing safety for the driver and passengers, as well as reducing the public cost of society safety, especially catering the demands of elderly drivers.

According to Saito et al (2022), the number of accidents involving elderly drivers who disobey stop signs is increasing, especially due to failure or inability to identify potential conflict with other road users at stop-sign controlled intersections. The same study concluded that braking-assistance intervention systems are effective in helping drivers avoid failure or inability to search for potential conflict and further stop-sign violations. However, the author also concludes that cognitively impaired drivers with high delta TMT scores may not be able to use the time the systema makes available to search for conflicts, indicating that braking intervention systems alone may not be effective at compensating for the improper and unsafe behaviors exhibit by cognitively impaired drivers.

According to Tanaka et al. (2020), there is a high disparity that can be observed in the biological functions of individuals of the same age, which means it is inappropriate to determine driving capability based solely on age.

Previous research has suggested that encouraging self-awareness in driving behavior reduces the impact of aging on driving and driving with fellow passengers has the potential to reduce the traffic accident rate. Thus, this study proposed a driver agent in the form of a compact communication robot and a smartphone to encourage safer driving by helping drivers recognize their own behavior in daily life.

Tanaka et al. (2020) proposed a driving support system to provide feedback to the driver to improve self-awareness and consequently reduce driving mistakes. The author assessed data from traffic accidents involving elderly drivers, identifying common situations where such accidents occurred, i.e., stop sign-controlled intersections, avoidance of parked cars, avoidance of pedestrians, and traffic merging. Such situations were monitored in the context of parameters: time to collision (TTC) for an intersection; stopping position in relation to intersection; instantaneous speed in relation to road speed limit; time between speed check events; accelerating level. By supporting the elderly drivers with warnings in the specified conditions, the authors concluded that improvement of safety conditions was possible, indicating that the analyzed parameters held relation to the unsafe behavior of elderly drivers.

2.2. Driver behavior in microsimulation

Microscopic traffic simulation models are the result of several sub-models operating simultaneously to describe the driving behavior of a specific vehicle given its relationship with surrounding vehicles, infrastructure characteristics and intersection control rules. Among the sub-models involved in the microsimulation process, special mention must be given to the following models: car-following model, lane-change model, and gap-acceptance model. These are highly relevant in resulting driver behavior modeling.

As this study aims at identifying the set of parameters which will offer a better representation of the driving behavior associated to elderly drivers, it becomes necessary to detail each of the sub-models listed above. Future steps in modeling the elderly drivers' case will be conducted using the microsimulation software VISSIM, therefore, its respective sub-models are discussed here. The software selection is given to its availability for use by the authors.

The Wiedemann model is used as car-following model in VISSIM. This is a so-called psycho-physical model based on the assumption that the driver will be in one of four possible driving modes: free driving, following, approaching, or braking, as described in Table 1.

Table 1 – Driving modes in the Wiedemann car following model

Driving mode	Description
Free Driving	There is no influence from leading vehicles. The driver will use its maximum acceleration rate to achieve the desired speed.
Following	Leading vehicles interfere in the driver´s speed, causing it to continuously adjust its acceleration rate to ensure constant safety distance to the leading vehicle.

Approaching	The safety distance to the leading vehicle is progressively reducing, causing the driver to decelerate (brake) to try and recover the safety distance.
Braking	The distance to the leading vehicle is below the emergency safety distance, causing the driver to decelerate (up to the maximum deceleration rate) to avoid a collision.

The determination of the current driving mode is performed based on a set of thresholds, presented in Table 2. These thresholds are crucial for the representation of elderly drivers, especially regarding its relation to the decrease in driver perception towards distance, speed, and acceleration.

Table 2 - Thresholds for driving modes in Wiedemann car following model

Threshold	Description
AX	Desired distance to the leading vehicle in standstill condition.
ABX	Minimum distance to the leading vehicle at equivalent speed.
SDX	Maximum distance to the leading vehicle at equivalent speed.
SDV	Minimum distance to the leading vehicle at specific speed to enter approaching mode.
CLDV	Minimum distance to the leading vehicle at specific speed to enter following mode.
OPDV	Maximum distance to the leading vehicle at specific speed to leave following mode.

The Wiedemann model is presented in two formats in VISSIM. The first is Wiedemann 74, which is recommended to urban traffic conditions. Its mathematical definition is given by Eq 1

$$u_n(t+\Delta t) = \min\left\{\begin{matrix} 3.6\left(\frac{s_n(t)-AX}{BX}\right)^2 \\ 3.6\left(\frac{s_n(t)-AX}{BX\times EX}\right)^2, u_f \end{matrix}\right\} \qquad \text{Eq. 1}$$

where $u_n(t+\Delta t)$ is the driving speed in the next simulation time step; BX and EX are random parameters.

Additionally, the mathematical definition for the desired safety distance is given by Eq 2.

$$d_{saf} = ax + (bx_{add} + bx_{mult} \times z) \times \sqrt{v} \qquad \text{Eq. 2}$$

where v is the vehicle speed, z is a normally distributed value in the range [0,1], set around 0.5 with a standard deviation of 0.15, ax is the desired distance between two stationary vehicles, corresponding to AX in Table 1, bx_{add} is the additive part of the coefficient related to the speed influence in the safety distance, bx_{mult} is the multiplicative part of the coefficient related to the speed influence in the safety distance.

The set of configurable parameters of the car following model Wiedemann 74 in VISSIM is presented in Table 3, which basically only allows for the setting of the safety distance. Although this setting shows considerable influence in the traffic density and therefore allows for the calibration of level of service conditions, it gives limited opportunities to pursue the necessary adjustments to represent elderly drivers.

Table 3 – Configuration parameters for Wiedemann 74 car following model in VISSIM

Parameter	Description
Look ahead distance	The distance that a driver can see ahead of his own vehicle and still be able to react to actions made by surrounding drivers. Observed vehicles: Controls a driver's ability to predict other vehicle's actions and respond to them. The higher the value the more vehicles can be observed.
Look back distance	Equivalent to the Look ahead distance but refers to the distance a driver can see behind his vehicle.
Temporary lack of attention	Refers to the period of time during which a driver is unable to respond to changes in the preceding vehicles driving behavior. Duration and Probability defines how long respectively how often the lack of attention occurs.
Smooth closeup behavior	If active, a driver will reduce his speed more evenly when approaching a static obstacle.

Standstill distance for static obstacles	Only applicable when Smooth closeup behavior is active. Determines at wat distance from a static obstacle a driver should stop. Concerned with AX in Table 1.
Additive part of safety distance	Corresponds to the BXadd coefficient.
Multiplicative part of safety distance	Corresponds to the BXmult coefficient.

In Wiedemann 99, which is usually recommended for highway traffic, the mathematical definition is more detailed, including additional coefficients, as presented in Eq. 3

$$u_n(t+\Delta t) = \min\left\{\begin{matrix} u_n(t)+3.6\left(\frac{CC8-CC9}{80}\times u_n(t)\right)\Delta t \\ 3.6\left(\frac{s_n(t)-CC0-L_{n-1}}{u_n(t)}\right) \end{matrix}, u_f\right\} \quad \text{Eq. 3}$$

Where $u_n(t+\Delta t)$ is the speed for the next simulation time step, CC0 is the standstill distance, CC8 is the standstill acceleration, CC9 is the acceleration at 80km/h, Ln-1 is the effective length of vehicle n-1 (which is the leading vehicle), Sn(t) is the spacing between vehicles n and n-1 at simulation step t.

The second sub-model of interest is the lane change model, which is divided into two logics, which depend on whether the maneuver is mandatory or discretionary. The mandatory lane change maneuver happens when the driver must react to route-induced turn, the end of the current lane due to a lane reduction on the road or a traffic disruption. The discretionary lane change happens when the driver tries to reposition the respective vehicle in order to achieve its desired speed. Both logics involve behaviors identified in the literature review as characteristic of the behavioral changes observed in elderly drivers. The parameters for lane change in VISSIM are presented in Table 4.

Table 4 - Configuration parameters for Wiedemann 99 car following model in VISSIM

Parameter	Description
General behavior	Determines the type of overtaking to be allowed. The options are either Free Lane Selection, where overtaking is allowed in any lane, or Right Side Rule.
Necessary lane change (route)	Deceleration thresholds for the own vehicle and the trailing vehicle to adjust the aggressiveness of the necessary lane change can be adjusted. The Maximum and Accepted deceleration defines the range of deceleration allowed to perform a lane change. The reduction rate 1 m/s^2 per distance determines the pace at which the Maximum deceleration will change in relation to the emergency stop distance.
Waiting time before diffusion	The maximum time a vehicle will stay at the emergency stop position waiting to perform a necessary lane change. If the waiting time exceeds the specified value, the vehicle will be removed from the network.
Minimum headway	The minimum remaining distance required between two vehicles after a lane change.
To slower lane if collision time	The minimum time headway that must be available on the slower lane in order to make a faster vehicle traverse to it.
Safety distance reduction factor	Determines how much the safety distance between vehicles should be reduced during lane change.
Maximum deceleration for cooperative braking	Decides if a trailing vehicle will start cooperative braking, i.e., let a leading vehicle change from to its own lane, or not by reducing his speed. The higher the value of this parameter is, the higher is the probability of a lane change to take place.
Overtake reduced speed areas	Determines if lane-dependent speed restrictions will be considered. If this parameter is not included, vehicles will not perform a lane change upstream a reduced speed area, and any reduced speed restrictions in the target lane will be ignored.
Advanced merging	If active, this option allows more vehicles to change lanes at an earlier point, and by doing so also decreases the risk of vehicles stopping to wait for a merging possibility. This is done by taking the speed of the adjacent vehicles into account in addition to the emergency stop distance. If not active, a vehicle will not break or cooperate with another vehicle within 50 m ahead.
Consider subsequent static routing decisions	Determines whether a vehicle leaving a static route will consider other routing decisions ahead when choosing lane.
Cooperative lane change	Determines whether a vehicle leaving a static route will consider other routing decisions ahead when choosing lane.
Lateral correction of rear end position	Determines whether a vehicle leaving a static route will consider other routing decisions ahead when choosing lane.

The third sub model of interest to reproduce the changes in driving behavior of elderly drivers is the lateral behavior model, which configured by the parameters presented in Table 5 in VISSIM.

Table 5 - Configuration parameters for lateral behaviour in VISSIM

Parameter	Description
Desired position at free flow	The vehicle's lateral position within its lane during free flow movement.
Keep lateral distance to vehicle on next lane	If active, vehicles adapt their lateral position to the vehicles in the adjacent lane by keeping the Lateral minimal distance.
Diamond shape queue	Vehicles will be represented as rhombuses instead of rectangles, resulting in a more realistic shape of a built-up queue.
Consider next turn direction	If selected, vehicles will not overtake a vehicle on the same lane if there is a risk for collision at the subsequent turning connector.
Collision time gain	The minimum time gain to be met between a vehicle and an obstacle ahead to justify a change in lateral movement.
Minimum longitudinal speed	The minimum longitudinal speed required for a vehicle to move laterally
Time between direction changes	The minimum simulation time between two lateral movements in opposite directions. Not applicable for lateral movements during lane change.
Default behavior when overtaking vehicles on the same lane or adjacent lanes	Overtake on same lane: Allow or prevent vehicles in non-lane bound traffic to overtake on the same lane, either to the left, right or both. Minimum lateral distance: The distance that must be available between vehicles while overtaking on the same lane.
Exceptions for overtaking vehicles of the following vehicles classes	With this option, vehicle classes with a driver behavior that differs from the default one can be defined.

Based on the description of the sub-models, the configuration parameters can be set to represent the basic characteristics of elderly driving behavior, pending the adjustment of such parameters in the calibration process.

More complex characteristics, such as variable behavior parameters and specific relationships between parameters such as acceleration rates and distance to intersection conflict point, can be implemented by the codification of specific driving behavior libraries for the simulation software.

2.3. Safety assessment in microsimulation

The change in safety due to elderly drivers' degradation of driving related-cognitive abilities and reactions can be quantified by safety assessment indicators must be incorporated into the simulation model.

Simulation models have been widely used around the world to evaluate the performance of different traffic facilities and management strategies for efficient and sustainable transportation systems. One of the keys factors for ensuring the reliability of the models in reflecting local conditions is the calibration and validation of microsimulation models. Most of the existing calibration efforts focus is on the experimental designs of driver behavior and lane-changing parameters(Farrag et al., 2020).

Darzentas et al. (1980) presented one of the first studies to investigate the potential of microscopic simulation in traffic safety and traffic conflicts analysis. Since then, development in human behavior modeling has gained interest, as well as real time vehicle data acquisition (Cunto and Saccomanno, 2007; Cunto and Saccomanno 2008; Saccomanno et al., 2008; Yang et al., 2010; Cheol and Taejin, 2010).

According to Mahmud at al. (2019), the simulation-based approach for the safety analysis permits a dynamic diagnose of the potential for accident occurrences. The literature focus on vehicle-to-vehicle collisions. Accidents involving vulnerable road users such as motorcycles, bicycles, and pedestrians have not been extensively simulated.

Most used indicators for the assessment of safety issues using microsimulation include Time-to-Collision (TTC), Headway (H), Post-Encroachment, Unsafe Density, Time Integrated Difference of Space Distance and Stopping Distance (TIDSS).

Each indicator is better suited for specific collision types. According to Mahmud et al. (2019), the Time-To-Collision indicator is suitable for rear-end, head-on, turning/weaving, hit objects/parked vehicle, crossing and hit pedestrian. The Headway indicator is suitable for Rear-end mainly, other such as turning and hit objects/parked vehicle. The Post-Encroachment Time (PET) is Mainly for right angle or crossing crash, hit pedestrian rear end, and head on.

The indicators Unsafe Density (UD) and Time Integrated Difference of Space Distance and Stopping Distance (TIDSS) are adequate for rear-end collisions.

Since safety indicators are not part of the standard features of commercially available microsimulation software, its implementation requires the design, coding, and calibration of additional scripts.

Cunto (2008) applied a safety performance evaluation model in VISSIM using as input parameters: mean and standard deviation of desired speed, desired deceleration, observed vehicle ahead, standstill distance (for stopped vehicles), headway time, following variation, threshold for entering "following" mode, positive "following" threshold, speed dependency of oscillation, minimum distance to lead vehicle (minimum headway), safety distance reduction factor, and maximum deceleration for cooperative breaking.

Yang (2012) implemented a safety assessment model based on surrogated indicators in PARAMICS, calibrating the model within a feasible range for each parameter, in terms of low and high levels. The major analysis parameters include mean target headway, mean driver reaction time, minimum gap, queue gap distance, queue speed, link headway factor, link reaction factor, signpost, speed memory, driver aggressiveness and driver awareness.

Chiara, et al. (2009) used a Risk Index based model to implement a safety assessment in AIMSUN focusing on the impact of intervehicle communication systems. The index considered the time required for the following vehicle to stop completely; the relative speed between the following vehicle and the leading vehicle; and the distance between the head of the following vehicle and the rear of the leading vehicle. Stopping time is calculated by the combination of three factors, driver's reaction time; vehicle's characteristics, such as speed, braking capacity, and condition of tires; and the road conditions, such as dry, wet, slush, snow, or ice.

The changes in safety conditions due to the representation of elderly drivers in microsimulation models can be achieved by a set of well-established safety performance indicators were considered as follows:

The indicator Time to Collision (TTC) is defined as the time that remains until a collision between two vehicles would occur if the course and speed difference are maintained. The indicator TTC is calculated as,

$$TTC_i^n = \frac{x_{i-1}^n - x_i^n - l_{i-1}}{v_i^n - v_{i-1}^n} \qquad \text{Eq. 5}$$

where n is the discrete instant of study, xi[n] is the position of the vehicle i, vi[n] its speed, and xi−1[n], vi−1[n], and li−1 are the position, speed, and length of the preceding vehicle, respectively.

The indicator TTC will provide the situation regarding two vehicles during their trip, however it will not identify the unsafe situation by itself. For that, it is necessary to choose an adequate critical threshold to be compared to the indicator in each simulation step. Moreover, the decision for the critical threshold must consider the situation in analysis, e.g., urban intersections or highways.

The indicator Time Exposed Time to Collision (TET) describes the total time spent in safety-critical situations, i.e., the time travelled under the safe TTC threshold.

$$TET_i = \sum_{n=0}^{N} (\delta \times \tau_{sc}) \qquad \text{Eq. 6}$$

where τsc is the time step for which the TTC is assumed to be constant, and δ is a switching variable which is 1 when TTC for the vehicle i at the discrete instant n is smaller than the threshold T T C∗ and 0 otherwise.

$$\delta = \begin{cases} 1, & if\ TTC^* < TTC_i^n \\ 0, & otherwise \end{cases}$$

where τsc is again the time step for which the TTC is assumed to be constant, n is the discrete instant, δ is a switching variable, TTC∗ is the selected threshold, and TTCi[n] is the TTC value at instant n. (TTC∗ − TTCi[n]) calculates the IR similarly, therefore, TIT does not need further transformation.

The indicator Time Integrated Time to Collision TIT considers the time spent under a TTC threshold, integrating TTC overtime in order to consider the level of conflict.

$$TIT_i = \sum_{n=0}^{N}[(TTC^* - TTC_i^n) \times \delta \times \tau_{sc}] \qquad \text{Eq. 7}$$

The indicator Modified Time to Collision (MTTC) considers the positions and the speeds of the involved vehicles in order to calculate the time remaining for a collision to happen, taking into account the vehicles' accelerations.

$$MTTC_i^n = \frac{-\Delta v^n \pm \sqrt{(\Delta v^n)^2 - 2\Delta a^n \Delta x^n}}{\Delta a^n} \qquad \text{Eq. 8}$$

where Δx[n] is the distance between the leading vehicle i − 1 and the following, vehicle i at instant n, Δx[n] = xi−1[n] − xi[n], Δv[n] is the relative speed, Δv[n] =vi−1[n] − vi[n], and Δa[n] is the relative acceleration, Δa[n] = ai−1[n] − ai[n]. The plus-minus sign (±) provides two solutions for a single MTTC, the appropriate choice is that which yields the minimum positive result.

The indicator Crash Index (CI) uses the estimation of the kinetic energy of the vehicles to assess the power of a potential collision.

$$CI_i^n = \frac{\left(v_{i-1}^n + a_{i-1}^n \times MTTC_i^n\right)^2 - \left(v_i^n + a_i^n \times MTTC_i^n\right)^2}{2 \times MTTC_i^n} \qquad \text{Eq. 9}$$

where v[n], a[n], and MTTC[n] are as just explained above. For a more precise calculation, the inclusion of the vehicles' weight would be necessary. However, since this information is generally unknown, the mass of the automobiles is assumed to be constant and not included in the formula.

The indicator Proportion of Stop Distance (PSD) considers a ratio between the remaining distance to the potential collision point and the minimum possible stopping distance, addressing the collision risk from a distance-based perspective.

$$PSD_i^n = \frac{RD_i^n}{MSD_i^n} \qquad \text{Eq. 10}$$

$$RD_i^n = TTC_i^n \times v_i^n \qquad \text{Eq. 11}$$

and

$$MSD_i^n = \frac{\left(v_i^n\right)^2}{2d} \qquad \text{Eq. 12}$$

The indicator Difference of Space Distance and Stopping Distance (DSS) considers that an emergency stop will be performed by both vehicles, therefore, both minimum stopping distances are addressed.

$$DSS_i^n = \left(\frac{{v_{i-1}^n}^2}{2\mu g} + d_{i-1,i}^n\right) - \left(v_i^n \times R + \frac{{v_i^n}^2}{2\mu g}\right) \qquad \text{Eq. 13}$$

where n is the discrete instant of study, vi[n] and vi−1[n] are the speeds of the following and preceding vehicle, respectively, μ is the friction coefficient, g is the gravity acceleration, R is the reaction time of the following driver, and di−1,i[n] is the distance between both vehicles, defined as di−1,i[n] = xi−1[n] − xi[n] − li−1, where xi[n] and xi−1[n] are the positions of the following and preceding vehicle, respectively, and li−1 is the length of the leading vehicle.

3. Representing elderly driving behavior in microsimulation

The review of the literature on the changes in driving behavior due to the aging process indicates that the most behavior characteristics can be directly related to standard configuration parameters used by commercially available software, as presented in Table 2. This is the case for the increased duration and frequency of checking guidance systems, which can be translated as an increased value for the parameter period of lack of attention.

Table 6 - Behavior changes identified in literature.

Study	Observed changes	Relation to other elements	Related standard parameter
Pauzie and Marin-Lamellet (1989)	Increased duration and frequency of checking guidance systems	All other elements	Temporary lack of attention on the road
Hosokawa et al. (2008)	Increased number of verifications before starting turns	Conflicting vehicles, intersection position	Gap acceptance confirmation
Griffiths and Gillespie (2004); Mammar et al. (2006); Forsyth and MacLean (2006); Mulder and Abbink (2008)	Difficult in maintenance of lateral position of lane during curves	Network geometry	Position in lane
Akagi and Raksincharoensak (2015)	Higher than expected speed near intersections, lower deceleration rate near intersections	Intersection position	Car following related headway parameters
Saito et al (2022)	Failure to identify potential conflicts at stop sign-controlled intersections	Conflicting vehicles, intersection position	Look ahead distance
Tanaka et al. (2020)	Unsafe headway near intersections, close stop position in relation to intersection, higher instantaneous speed in relation to speed limit, longer interval between speed checks	Lead vehicles, intersection position	Headway, desired speed, speed variance parameters that are variable considering distance to intersections
Stelmach & Nahom, 1992	Longer reaction time and less precision	Conflicting vehicles, intersection position	Temporary lack of attention on the road
Nishida (1992)	Slower speeds	Lead vehicles, intersection position	Look ahead/back distance
Nishida (1992)	Longer headways	Lead vehicles, intersection position	Look ahead/back distance
Nishida (1992); Waard et al (2009)	Unsafe gap acceptance	Conflicting vehicles, intersection position	Gap acceptance confirmation

Jobanputra and Vanderschuren (2012) consolidated a list of parameters related to microscopic models along with their typical range of values, which is adapted in Table 7. They show the interval usually considered during the development of microsimulation models, rather than an specific value, indicating that it is necessary to analyze the range to be used as representation of the deviation caused by the cognitive degradation in elderly drivers.

Table 7 – Main behavioral parameters used in commercially available microsimulation software.

Parameter	Type	Comments	Typical value
Desired speed	Behavioral and physical	Link-specific, speed limit regulation based, road layout influenced, agent density influenced.	Probabilistic distribution with mean value around the legal speed limit
Desired headway	Behavioral	May be expressed in units of time or distance	1.5–2.5s; 5.96s for truck; 6.5m

Reaction time (s)	Physiological	May not be explicitly represented (may be inherent in the simulation interval)	0.57-3.0
Rate of acceleration (m/s2)	Behavioral (constrained by vehicle performance)	May distinguish between normal rate of acceleration and maximum rate of acceleration, may differ depending on vehicle type	1.5-3.6 (max); 0.9-1.5 (normal) 1.2-1.6 (buses)
Rate of deceleration (m/s2)	Behavioral (constrained by vehicle performance)	May distinguish between normal deceleration and emergency braking, may differ by vehicle type	1.5-2.4 (emergency) 0.9-1.5 (normal) 3.0 (theoretical)
Critical gap (s)	Behavioral	From the back of one vehicle in the target stream to the front of the following vehicle in that stream	3.5-8.5
Stimulus required to induce use of the reduced gap	Behavioral	Time spent waiting for acceptable gap or number of rejected gaps	Various
Minimum gap (s)	Behavioral		1.0
Lane change	Behavioral and political	May simply reflect traffic regulations but may vary depending on enforcement policy	Various
How far ahead the driver anticipates the need to change lanes	Behavioral and political	The behavioral element may be constrained by sight lines, etc.	1 to 2 links or 500m
Minimum acceptable gap when changing lanes	Behavioral	As in gap-acceptance model	Usually represented by a minimum headway in distance and time, which vary according to the conflicting flow speed.
Temporary period of lack of attention	Behavioral	May influence decision making process during simulation	0 to 3s

As the parameters change according to the location of the simulated situation, it is expected that the deviation for elderly driver parameters also be related to the location and possibly to the age distribution of the drivers. Those dependencies will be further studied in the future steps of this research.

4. Assessing safety performance indicators related to the behavior of elderly drivers in microsimulation

The possibility of representing elderly drivers in microsimulation models allows the safety assessment of traffic scenarios considering a higher participation of this population group. In Japan, for example, the population in rural areas and small communities, far from the large urban centers, tend to be comprised mostly by this age group.

The proper adjustment in traffic signal controls, as well as in road design to ensure necessary visibility and allow for adequate reaction time, specially in intersections, can potentially reduce the probability of traffic accidents, creating a more inclusive environment for elderly drivers.

Based on the safety performance indicators addressed in the literature review, a relation between those indicators and the expected behavioral changes of elderly drivers can be established, as shown in Table 8. The safety indicator selection is based on the adequacy of the respective formulation to the situation to be analyzed, such as same lane car following conflict, perpendicular vehicle approach at intersections, or single car approaching a intersection.

Table 8 – Relation between elderly drivers identified behavior changes and safety indicators

Elderly driver behavior change	Driving behavior parameter	Safety indicator
Increased duration and frequency of checking guidance systems	Temporary lack of attention	TET, MTTC
Increased number of verifications before starting turns	Gap acceptance	TET, MTTC
Difficult in maintenance of lateral position of lane during curves	Lateral behavior	ACI

Higher than expected speed near intersections, lower deceleration rate near intersections	Intersection reaction, acceleration control	TTC, MTTC, PSD
Failure to identify potential conflicts at stop sign-controlled intersections	Intersection reaction	TTC, MTTC, PSD
Unsafe headway near intersections, close stop position in relation to intersection, higher instantaneous speed in relation to speed limit, longer interval between speed checks	Intersection reaction, acceleration control, temporary lack of attention	TTC, MTTC, PSD, DSS
Longer reaction time and less precision	Temporary lack of attention	TET, MTTC
Slower speeds	Acceleration control	MTTC
Longer headways	Following threshold	MTTC
Unsafe gap acceptance	Gap acceptance	TET, MTTC

The calculation of safety performance indicators does not interfere with overall simulation results, i.e., the vehicles in the simulation do not react to the safety indicators. Therefore, the implementation of the safety indicators calculation can be performed using the log of the necessary variables for all vehicles during the simulation period.

In the next steps of this research, the calculation procedure for the safety indicators will be implemented in a python script to a case study yet to be decided.

5. Implications for microsimulation models

5.1. Traffic composition

The methodology for the representation of elderly drivers in microsimulation models is based in the definition of a special type of driver for each vehicle class with the objective to have, for the same vehicle class, two type of drivers: standard driver and elderly driver. For example, in a simulation that considers the vehicles class *Car*, it would be necessary to divide that class into two new classes: *Car–Standard* and *Car-elderly*. In order to proceed with such configuration, it becomes necessary to specify the proportion or each driver type within the proportion of the vehicles class *Car*.

Different possibilities can be considered to obtain this information, from the analysis of secondary data, such as driver license database for the study area, to interview a sample of the drivers in the study area to create a distribution of age groups within the drivers.

Although the format of the data acquisition process is outside the scope of this paper, the issue will be addressed in future research, when the implementation of the proposed methodology will take place.

5.2. Calibration

The process for the calibration of microsimulation models usually involves the assessment of the reproducibility of aggregated characteristics such as traffic volume per time interval, average travel time in a road section, or traffic density, using optimization techniques to adjust several behavioral and physical parameters in the search for the best adherence to reference values. In this process, parameters such headways and gap acceptance are usually set with little regard to the real values since those parameter inputs are not part of the surveyed data for the project. In this instance, it will be required that a specific class of drivers is reserved for the representation of elderly or that the optimization algorithm for calibration considers special ranges in the adjusted parameters to ensure elderly representation.

However, this process is not sufficient to ensure the proper adjustment of the driving behavior of a sub-group of the drivers. For that, it is expected that detailed data collection of vehicles equipped with accelerometers and other high-resolution devices will be necessary, similar to the process originally used to derive the original car following models.

Alternatively, the results of the safety performance indicators could be compared to statistics relating to recurring traffic accidents in specific intersections or other locations with significant history of traffic accidents, with the objective of improving the adherence between calculated accident risk and real-world statistics.

This issue will be addressed in future research.

5.3. Model sensibility

The evidence from the literature review is compelling in establishing the necessary framework for the representation of elderly drivers. Given the limitations on the parametrization related to the vehicle location in relation to the position of the intersections, which requires further customization, it is possible to categorize the implementation of such parameters in driver specific parameter adjustments and infrastructure related parameter adjustments.

The level of sensibility obtained for each category of parameters is yet to be determined in a further study to explore the adequate range suitable for each parameter, considering the safety assessment possibilities.

6. Conclusions

Driving behavior influenced by the cognitive degradation commonly observed in elderly drivers can be represented in a basic level in microsimulation models by the configuration of specific standard parameters in commercially available software, specially in VISSIM, as presented in this study, and, in more complex level, by implementation of additional functionality through customized driver behavior logic.

The safety assessment of the traffic conditions considering a percentage of elderly drivers opens the possibility of using microsimulation to evaluate the impact in reducing traffic fatalities when adopting project interventions, inclusive intersection design, onboard ITS systems, and progressive insertion of autonomous vehicles in the traffic composition. Moreover, the impact of the increasing participation of the target age group in the driver poll can be assessed, along with the respective changes in the traffic safety conditions.

References

Akagi, Y. and Raksincharoensak, P. 2015 An Analysis of an Elderly Driver Behaviour in Urban Intersections based on a Risk Potential Model. In Proceedings of 41st IECON Annual Conference of the IEEE Industrial Eletronics Society. Yokohama, Japan.

Bayrak, O.Ü.; Bayata, H.F. Multi-criteria decision-based safety evaluation using microsimulation. Proc. Inst. Civ. Eng. Transp. 2020, 173, 345–357.

D.B. Chiara, et al. 2009 Assessing the effects of inter-vehicle communication systems on road safety, IET Intelligent Transportation Systems. 3 pp. 225.

F.J.C. Cunto, 2008 Assessing Safety Performance of Transportation Systems Using Microscopic Simulation, in Civil Engineering, Canada, University of Waterloo.

Griffiths, P. and Gillespie, R.B. (2004) "Shared control between human and machine: Haptic display of automation during manual control f vehicle heading". In Proceedings of the 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Chicago, USA, pp. 358-366.

H. Yang, 2012 Simulation-Based Evaluation of Traffic Safety Performance Using Surrogate Safety Measures, Rutgers University-Graduate School-New Brunswick, New Brunswick, New Jersey, USA, p. 176.

Japan, National Police Agency 2019 "Traffic accidents situation in 2019," National Police Agency, Tokyo, Japan, 2019. [Online]. Available: https://www.e-stat.go.jp/stat-search/files?page=1&layout=datalist&toukei=00130002&tstat=000001027458&cycle=7&year=20190&month=0&stat_infid=000031910507&tclass1val=0

K. J. Manning, P. P. Barco, and M. T. Schultheis 2019 Driving Evaluation in Older Adults. Cham, Switzerland: Springer, pp. 231–251.

Mackenbach, J.P., and van der Maas, P.J. (2008) “Volksgezondheid en Gezondheidszorg”, pp. 122-123. Elsevier Gezondheidszorg, Maarssen.

Mammar, S., Glaser, S. and Netto, M. (2006) “Time to Line Crossing for Lane Departure Avoidance: A Theoretical Study and an Experimental Setting”. IEEE Transactions on Intelligent Transportation Systems, vol 7, pp. 226-241.

Mulder, M., Abbink, D.A., and Boer, E.R. (2008) “The effect of haptic guidance on curve negotiation behavior I young experienced driver”. In Proceedings of the IEEE International Conference on Systems, Man Cybernetics, Singapore, pp. 804-809.

Matsumoto, K. , Kaneko, M. , Hashimoto, H., Koide, M., The 38 Infrastructure Planning Meeting of JSCE, 2008

Pauzie and C. Marin-Lamellet, "Analysis of aging drivers' behaviors navigating with in-vehicle visual display systems," Conference Record of papers presented at the First Vehicle Navigation and Information Systems Conference (VNIS '89), 1989, pp. 61-67, doi: 10.1109/VNIS.1989.98741.

R. Segal, M. White and L. Robinson, 2019“Age and driving,” helpguide.org, July 2019.

S. Bao and L. N. Boyle, 2008 Driver performance at two-way stop-controlled intersections on divided highways. Transp. Res. Rec., Journal of Transportation Research Board, vol. 2069, no. 1, pp. 26–32, Jan. 2008.

S. Chihuri, T.J. Mielenz, C.J. DiMaggio, M.E. Betz, C. DiGuiseppi, V.C. Jones, and G. Li (2016) “Driving cessation and health outcomes in older adults,” Journal of the American Geriatrics Society, Vol.46, No.2, 2016, pp. 332–341.

S. Lyman, S.A. Ferguson, E.R. Braver, and A.F. Williams 2002 Older driver involvements in police reported crashes and fatal crashes: Trends and projections, Injury Prevention, Vol. 8, No. 2, June 2002, pp. 116–120.

Saito, Y. et al (2021) “Effectiveness of a Driver Assistance System with Deceleration Control and Brake Hold Functions in Stop Sign Intersection Scenarios” IEEE Transactions on Intelligent Transportation Systems.

Tanaka, T., Fujikake, K., Yoshihara, Y., Karatas, N., Shimazaki, K., Aoki, H., and Kanamori, H. (2020) “Analysis of Distraction and Driving Behavior Improvement Using a Driving Support Agent for Elderly and Non-Elderly Drivers on Public Roads”. IEEE Intelligent Vehicles Symposium (IV). Las Vegas, USA.

Triantaphyllou, E. 2000 Multi-Criteria Decision Making Methods: A Comparative Study; Springer: Boston, MA, USA.

S. Karceski et al. (2011) Driving after a stroke. Neurology (2011).

Albert, G., Lotan, T., Weiss, P., & Shiftan, Y. (2018). The challenge of safe driving among elderly drivers. *Healthcare Technology Letters*, *5*(1), 45–48. https://doi.org/10.1049/HTL.2017.0002

Amiri, A. M., Sadri, A., Nadimi, N., & Shams, M. (2020). A comparison between Artificial Neural Network and Hybrid Intelligent Genetic Algorithm in predicting the severity of fixed object crashes among elderly drivers. *Accident Analysis & Prevention*, *138*, 105468. https://doi.org/10.1016/J.AAP.2020.105468

Broberg, T., & Dukic Willstrand, T. (2014). Safe mobility for elderly drivers—Considerations based on expert and self-assessment. *Accident Analysis & Prevention*, *66*, 104–113. https://doi.org/10.1016/J.AAP.2014.01.014

Chandraratna, S., & Stamatiadis, N. (2003). *Problem driving maneuvers of elderly drivers*. *1843*, 89–95. https://doi.org/10.3141/1843-11

Chipman, M. L., Payne, J., & McDonough, P. (1998). To drive or not to drive: The influence of social factors on the decisions of elderly drivers. *Accident Analysis & Prevention*, *30*(3), 299–304. https://doi.org/10.1016/S0001-4575(97)00107-3

de Waard, D., Dijksterhuis, C., & Brookhuis, K. A. (2009). Merging into heavy motorway traffic by young and elderly drivers. *Accident Analysis & Prevention*, *41*(3), 588–597. https://doi.org/10.1016/J.AAP.2009.02.011

DUC-NGHIEM, N., HOANG-TUNG, N., KOJIMA, A., & KUBOTA, H. (2016). TRAFFIC SAFETY OF ELDERLY ROAD USER: THE GLOBAL TREND AND THE JAPANESE CASE. *土木学会論文集 D3（土木計画学）*, *72*(5), I_1249-I_1264. https://doi.org/10.2208/jscejipm.72.I_1249

Farrag, S. G., El-Hansali, M. Y., Yasar, A.-U.-H., Shakshuki, E. M., & Malik, H. (2020). A microsimulation-based analysis for driving behaviour modelling on a congested expressway. *Journal of Ambient Intelligence and Humanized Computing*, *11*(12), 5857–5874. https://doi.org/10.1007/s12652-020-02098-5

Guo, A. W., Brake, J. F., Edwards, S. J., Blythe, P. T., & Fairchild, R. G. (2010). The application of in-vehicle systems for elderly drivers. *European Transport Research Review*, *2*(3), 165–174. https://doi.org/10.1007/S12544-010-0037-Y/FIGURES/1

Hong, K., Lee, K. M., & Jang, S. nang. (2015). Incidence and related factors of traffic accidents among the older population in a rapidly aging society. *Archives of Gerontology and Geriatrics*, *60*(3), 471–477. https://doi.org/10.1016/J.ARCHGER.2015.01.015

Inagaki, T., Harada, N., Kashiwa, Y., Takehira, S., & Kobayakawa, S. (2019). A Fundamental Analysis on Driving Behavior and Individual Property of Elderly Drivers Based on Driving Recorder Data. *Japanese Journal of Traffic Engineering*, *A*(2019.2), 208–216.

Kim, S. J., & Dey, A. K. (2009). Simulated augmented reality windshield display as a cognitive mapping aid for elder driver navigation. *Conference on Human Factors in Computing Systems - Proceedings*, 133–142. https://doi.org/10.1145/1518701.1518724

Marottoli, R. A., Cooney, L. M., Wagner, D. R., Doucette, J., & Tinetti, M. E. (1994). Predictors of automobile crashes and moving violations among elderly drivers. *Annals of Internal Medicine*, *121*(11), 842–846. https://doi.org/10.7326/0003-4819-121-11-199412010-00003

NAKANO, T., YAMADA, M., & YAMAMOTO, S. (2008). A METHOD FOR ASSESSING THE DRIVING ABILITY OF THE ELDERLY AND THOUGHTS ON ITS SYSTEMATIZATION. *IATSS Research*, *32*(1), 44–53. https://doi.org/https://doi.org/10.1016/S0386-1112(14)60199-0

Nishida, Y. (1999). Driving characteristics of the elderly: risk compensation of the elderly driver from the viewpoint of reaction behavior. *JSAE Review*, *20*(3), 375–380. https://doi.org/10.1016/S0389-4304(99)00030-2

Nishida, Y. (2015). Analyzing accidents and developing elderly driver-targeted measures based on accident and violation records. *IATSS Research*, *39*(1), 26–35. https://doi.org/https://doi.org/10.1016/j.iatssr.2015.05.001

Nishiuchi, H., Park, K., & Hamada, S. (2021). The Relationship between Driving Behavior and the Health Condition of Elderly Drivers. *International Journal of Intelligent Transportation Systems Research*, *19*(1), 264–272. https://doi.org/10.1007/s13177-020-00240-3

Odenheimer, G. L., Beaudet, M., Jette, A. M., Albert, M. S., Grande, L., & Minaker, K. L. (1994). Performance-Based Driving Evaluation of the Elderly Driver: Safety, Reliability, and Validity. *Journal of Gerontology*, *49*(4), M153–M159. https://doi.org/10.1093/geronj/49.4.M153

Oshima N. (2017). Traffic accidents and risk of elderly drivers 高齢ドライバーの交通事故とリスク. *Journal of the Japan Society for Safety Engineering*, *56*(3), 151–158. http://dx.doi.org/10.18943/safety.56.3_151

Parker, D., McDonald, L., Rabbitt, P., & Sutcliffe, P. (2000). Elderly drivers and their accidents: the Aging Driver Questionnaire. *Accident Analysis & Prevention*, *32*(6), 751–759. https://doi.org/10.1016/S0001-4575(99)00125-6

Persson, D. (1993). The Elderly Driver: Deciding When to Stop. *The Gerontologist*, *33*(1), 88–91. https://doi.org/10.1093/GERONT/33.1.88

Retchin, S. M., Cox, J., & Irwin, L. (1988). Performance-Based Measurements Among Elderly Drivers and Nondrivers. *Journal of the American Geriatrics Society*, *36*(9), 813–819. https://doi.org/10.1111/J.1532-5415.1988.TB04265.X

Sagar, S., Stamatiadis, N., Wright, S., & Green, E. (2020). Use of codes data to improve estimates of at-fault risk for elderly drivers. *Accident Analysis & Prevention*, *144*, 105637. https://doi.org/10.1016/J.AAP.2020.105637

Stelmach, G. E., & Nahom, A. (1992). Cognitive-Motor Abilities of the Elderly Driver. *Https://Doi.Org/10.1177/001872089203400107*, *34*(1), 53–65. https://doi.org/10.1177/001872089203400107

WOOD, J. M., & TROUTBECK, R. O. D. (1995). Elderly Drivers and Simulated Visual Impairment. *Optometry and Vision Science*, *72*(2). https://journals.lww.com/optvissci/Fulltext/1995/02000/Elderly_Drivers_and_Simulated_Visual_Impairment.10.aspx

Zhang, J., Lindsay, J., Clarke, K., Robbins, G., & Mao, Y. (2000). Factors affecting the severity of motor vehicle traffic crashes involving elderly drivers in Ontario. *Accident Analysis & Prevention*, *32*(1), 117–125. https://doi.org/10.1016/S0001-4575(99)00039-1