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A Systematic Review of Driver Ingress and Egress Using Passenger Vehicles: Considerations for Designers

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Abstract

Identifying ingress and egress strategies is an important area of research in the automotive sector. Determining ingress and egress strategies can lead to safer vehicle design that reduce fall risk and improve comfort. In this systematic review, we examined studies related to ingress and egress in passenger vehicles after searching for various databases. We found 9 primary articles (of 608), all published in English. The results of the present research synthesis show that participants reported challenges with doorway height, sill height during ingress and egress, as well as will width during egress. There are also various ingress and egress strategies employed by drivers. However, ingress and egress strategies did not differ significantly by sample characteristics (i.e., age, height) or vehicle type. Roof height was not a factor of ingress and egress strategies although a large sill width may increase the risk of adverse events during egress. Future studies need to incorporate larger and more heterogeneous samples (i.e., healthy versus non-healthy, younger versus older adults) and relate participant characteristics (i.e., age, gender, height, weight) and the use of hands (along with force measurements) with ingress and egress strategies. Additionally, changes in vehicle design should be modelled with comfort ratings using metrics and loss functions to determine the optimal point between comfort and safety. This is the first review of the ingress and egress literature to summarize important findings and provide directions for future research.

Keywords: Ingress; Egress; Drivers; Mock-up; Mobility; Kinematics; Ergonomics

Introduction

Ingress and egress are considered complex tasks due to the multitude of sensory and motor information necessary to access a vehicle. In fact, ingress represents the first interaction between the driver and the vehicle environment and, as such, manufacturers have begun to recognize that improving designs that affect how people enter and exit vehicles can influence customer perceptions of the car in question [1]. Understanding how drivers interact with the vehicle environment is critical to informing the design of specific features and, ultimately, satisfaction with the vehicle itself.

For the automotive industry, there is a shift expected in the types of consumers that will be purchasing their vehicles. Older drivers represent the fast growing segment of the car-buying population. The baby boomer generation have been responsible for the types of automobiles purchased in North America since they became of licensing age [2]. For example, when the boomers were having children, the minivan was popular in the 1980s. In 2011, the first of this generation began turning 65. Unfortunately, with advanced age often come changes in health and mobility [3]. As the number of older drivers rapidly increases [4], further efforts targeting driver safety need to be considered including how this generation access their vehicles. For example, 37,000 seniors in the United States are injured annually transferring into and out of a car, with over 40% of these injuries caused by falls [5]. A survey of over 1,000 drivers between the ages of 60 and 79 also highlighted challenges associated with egress (25%) and ingress (33%) as being a significant consideration in terms of vehicle design [6]. Clearly, incorporating design features that maximize the safety and mobility of this growing segment of customers is important to car manufacturers.

Several studies have used Digital Human Models (DHM) to examine specific movements related to ingress and egress. Translating complex motor tasks, like vehicle egress, to Digital Human Models (DHM) requires an in-depth analysis of users to ensure such models reflect the range of abilities inherent to the population. Designers are increasingly using digital mock-ups of the built environment in concert with DHMs as a means to reduce costs and speed-up the "time-to-market" of products [7]. DHMs can improve the ergonomics of a product but must be representative of actual users. Research on motion simulation and corresponding development of DHMs, such as SantosHuman (University of Iowa) and HumoSim (University of Michigan), have led to frameworks for classifying movement demands of vehicle egress and other applications (e.g., reach, posture, hand-eye coordination) that have potential beyond the automobile (e.g., military, manufacturing). More recently, the 'Handiman' project (University de Lyon, France) digitized the egress motion of older adults with the aim of creating more realistic DHMs. It is important to analyze the underlying physical capacities of users in order to capture their range of abilities and its effect on biomechanical interactions involving the automobile. While studies have examined movements specific to vehicle ingress and egress patterns, there has been no critical appraisal or systematic review of these findings. Such a review would be beneficial in order to highlight key findings as well as consider the limitations and gaps in current research. Hence, the purpose of this review is twofold: 1) to provide information on the most relevant ingress and egress patterns with respect to car geometry (i.e., seat height, sill width) and corresponding driver characteristics (i.e., age, height, weight) and; 2) summarize findings related to comfort and discomfort of ingress and egress. This review will provide considerations for vehicle design and future studies involving an older population.

Methods

Search strategy

A systematic literature search was performed to identify all published work pertaining to drivers and vehicle ingress and egress. The electronic databases PubMed, CINAHL (Cumulative Index to Nursing and Allied Health Literature), Engineering Village, OVID and SCOPUS, the authors' own files, and reference lists of included articles were searched. Key terms used for searching the electronic databases included: drivers, ingress/egress, vehicle entry/exit, motion analysis, ergonomics, and comfort/discomfort. The search strategy was designed for PubMed and adapted for the other databases (Table 1).

Database	Time Frame	No. of Hits	No. of Studies Selected	No. of Studies Selected After full-text review	Key Words/ MESH
PUBMED	None specified	75 a,b,c, d,e,f	8 selected; 6 retained after abstract review	6	Ingress; Egress, Drivers
CINAHL	None specified	8 a,c,d, g	8 selected; 4 retained after abstract review	4	Ingress; Egress, Drivers
Engineering Village	None specified	56 h,i,j,k,l ,m,n,o ,p	10 selected; 8 retained after abstract review	8	Ingress; Egress, Drivers
OVID	None specified	444	None selected	0	Ingress, Egress; Drivers
Scopus	None specified	25 c,e,h,i, j,m,n, o,p,q	10 selected; 9 retained after abstract review	9	Ingress, Egress; Drivers

Table 1: Literature Search Strategy. (Note: Article selected for full review. Bolded articles included in review; non-bold articles were removed from the review.) **(a) Causse et al. [8]; (b) Causse et el. [9]; (c) Chanteauroux et al. [10]; (d) Moore et al. [11];** (e) Olsen et al. [12]; (f) Smith and Williams [13]; (g) Carvalho and Soares [14]; (h) Reed et al. [15]; **(i) Causse et al. [1];** (j) Sabbah et al. [16]; (k) Reed and Huang [17]; **(l) Dufour and Wang [18]; (m) Menceur et al. [19];** (n) Coelho and Dahlman [20]; (o) Verriest [21]; **(p) Menceur et al. [22];** (q) Fisher et al. [23]

Inclusion and exclusion criteria

Articles were included in the review if they examined ingress and egress patterns of drivers. Studies were included if they were written in English, peer-reviewed, and presented results focusing on the driver cabin (rather than passengers). Studies involving commercial drivers were also excluded from this analysis.

Study selection

Two reviewers independently screened titles and abstracts of citations identified by the search against the inclusion criteria; discrepancies were resolved by discussion. The full text of citations that met the inclusion criteria or did not contain enough information to make a decision for inclusion were retrieved from the library. The full text of retrieved articles was then reviewed and, in cases of discrepancies, consensus was reached through discussion.

Data extraction and synthesis

Once the articles were selected, data were extracted and summarized in evidence tables. A table with discrete categories (research question, sample size and demographics, outcome variables, design, measurement, key findings) was created and pilot-tested on three studies. One reviewer completed the evidence tables for all the included studies, and another reviewer checked for accuracy.

Results

Literature search results

The search of five electronic databases yielded a total 608 citations. Of these, a total of 17 articles were included at the title and abstract level and full text was retrieved. As shown in Table 1, nine of the seventeen articles were selected while eight were not included for the following reasons: one study did not examine ingress/egress (n=1), four were not primary studies (e.g., methodology papers) and the three remaining studies examined ingress and egress in commercial drivers.

The studies outlined in supplementary Table 1 varied in their study population, assessment protocols and analysis of ingress and egress motions. All of these studies used an experimental design. Most research was conducted in France (7 of 9), with others taking place in Germany and the United States. Several studies assessed kinematics using the Vicon system in conjunction with force plates [1,7-9,16,19,22] and an H-point machine [1,7-9,16]. Other studies imported postures into RAMSIS to develop aspects of a digital mock-up [7,16]. For instance, one study used RAMSIS in the Computer-Aided Design (CAD) system to develop seat constructions in their vehicle mock-up [16].

Type of vehicle and movement patterns during ingress/egress

All nine studies examined ingress and egress although study objectives varied among included studies (see supplementary Table 1). Two studies examined ingress and egress across four different vehicle models: small and medium size vehicle, small commercial vehicle, and a minivan [19,22]. Their studies included 41 participants: 8 young and healthy adults (Mean age 26 ± 5); 19 older adults (Mean age 71 ± 5); and, 14 adults with various disabilities (Mean age 62 ± 13). Based on these analyses, ingress patterns were categorized into three phases: 1) door opening phase, 2) ingress movement adaptation phase (i.e., lifting of left leg from ground into the vehicle) and 3) seat phase (once both legs reach the ground floor). Analysis of these phases specified five ingress movement strategies (i.e., lateral sliding, backward motion, forward motion, trunk forward, trunk backward) and three egress strategies (i.e., head forward, parallel, and two foot). Although no specific ingress and egress strategy was observed by sample composition (i.e., young and healthy versus elderly versus pathological), kinematic data showed that healthy older adults tended to use a lateral sliding and backward motion approach during ingress and egress compared to the younger and pathological participants (both young and old). Additionally, kinematic data showed that ingress and egress strategies (i.e., lateral sliding, forward and backward motion, trunk forward and backward motion, head forward, parallel to the vehicle and two-foot egress) were not influenced by vehicle geometries despite the considerable differences across the four vehicle types [19].

Building on these findings, another study [7] examined ingress and egress motions in 7 younger (Mean age 26 ± 5) and 18 older participants (Mean age 71 ± 5) using the same four vehicle models as described in Menceur et al. [19,22]. According to their analysis, two primary egress strategies (instead of three) were identified: 1) left leg first and; 2) two legs out. However, the two legs out strategy were only used in 10% of cases (10 of 100 motions). Two older adults used this strategy across all four vehicle models when exiting vehicles (8 of 10 motions). The authors' postulated this egress strategy was linked to mobility, meaning those with balance problems required greater stability and, as such, were more likely to use the two foot out strategy [7].

In some cases, participants (mean age 33 ± 9; 14 men; 4 women) used their hands to help with both ingress and egress, which was found in more than 65% of observations [1]. Hand contact with the steering wheel was commonly observed, however, there was no hand contact with the sill and door frame. During egress, kinematic data indicated maximum contact force between the hand and the steering wheel occurred when the left foot was in contact with the ground. This force decreased when the right foot was placed on the ground outside of the vehicle and the driver's weight transferred from the right to left foot when exiting the vehicle. Location of the hand and corresponding forces were linked to the type of vehicle. For example, the placement of the hand on the steering wheel was at a higher contact point for the compact car when compared to the SUV. This attributed this difference to the need for higher/greater left hip effort to exit from the seat of the compact car, which is lower to the ground [1]. However, it is unknown (based on video inspection) whether participants used actual force or simply used their hands to propel their motions.

Roof height of vehicle

In a series of investigations [8,9], results indicated that roof height, measured to produce both comfort and discomfort in three different vehicles (i.e., small and medium car, minivan), was not impacted by vehicle features (i.e., seat and sill height, sill, roof and doorway width) and participant height (short women, mixed average and tall men) in 26 young and healthy volunteers. The findings show that a short person required almost the same roof height as a tall person during ingress and egress despite a 120 millimeter difference in sitting height between a short woman and a tall man. However, short participants (Mean height 1594 mm ± 28) adopted a more upright trunk position than tall participants (Mean height 1835 mm ± 23) when the head was passing under the roof from the lesser space between the seat and steering wheel [9]. Meanwhile, tall participants had greater trunk and neck flexion when the head passed under the roof than short participants [8]. Trunk flexion was linked to the distance between the seat and steering wheel rather than roof height which may explain why roof height was not affected by participant height. Based on this study, the difference between an acceptable and unacceptable roof height was determined to be 45 mm. This difference was more likely to affect head flexion during both ingress and egress.

Door sill design and seat orientation

More recently, sill width has become a focus for designers, particularly for egress [8]. Door height and width was identified as one of the most critical features to affect this motion [1]. Their experimental protocol involved examining ingress and egress across three sill heights and widths (narrow, medium, large). Large sill widths were found to increase the potential for the left leg to collide with the sill during egress. However, the effects of door opening were not evaluated, although the door was kept open at a set distance of 70 degrees across all vehicle configurations.

As well, seat orientation (upright versus recumbent positions with a 90 seat Angle) can also impact on the driver's range of motion during ingress and egress [11]. Range of motion of the right knee, right hip and trunk were greater during ingress and egress with a recumbent seat compared to an upright seat. Trunk range of motion was reported to be significantly greater during ingress than egress.

Examining comfort and discomfort associated with ingress and egress motion

Several studies have examined comfort and discomfort during ingress and egress [1,12,18]. One study compared ratings of discomfort using a questionnaire during ingress and egress across three vehicle models (small car, light utility vehicle and minivan) in 23 healthy volunteers [18]. However, discomfort ratings were not reported for the entire sample, only specific cases. A male participant of average height (1.75 metres) reported greater discomfort during egress than ingress, with the greatest discomfort in the light utility vehicle [18]. Another study used the CP50 Scale (Category Partitioning Scale 50) to assess comfort and discomfort [16]. The authors asked 18 participants (aged 22 to 63 years; body height from 158 to 192 cm) about ingress and egress of three different seat arrangements (stationary, tilted and swivelled). Results suggested that seat support (i.e., tilted and swivelled seats) was related to greater comfort rating compared to ratings for the stationary seat.

One study asked five subjects (one woman and four men; Mean age 35 ± 8) about their experiences getting in and out of 27 different vehicles of various size classes and manufacturers at an auto show (e.g., mini-compact cars, sub-compact cars, compact cars, midsize cars, sports cars, SUV's and utility vehicles) [1]. Participants were asked to get in and out of vehicles and comment about the general feeling of the vehicle and the design elements. Participants reported challenges with doorway height, sill height during ingress and egress, as well as will width during egress. The most critical design parameters determined to trigger a lower comfort rating included sill width above the ground (30%), sill width from the H-point (30%), seat height above the ground (16%), doorway width from H-point (13%), and doorway height from H-point (11%).

Discussion

A total of nine studies that examined vehicle ingress and egress of drivers were included in this review. These studies varied with regard to the size of the sample, as well as the demographics of those whose motor patterns and perceptions were captured, including age, gender, height, and stature as well as corresponding differences in experimental design. Such variability can affect the validity of their respective results. While there are corresponding trends in the data with respect to informing our understanding of factors that can influence ingress and egress, the results must be interpreted in light of the methods and design of these studies.

Assessing ingress and egress patterns provides an important step in considering how vehicles can be better design to improve both comfort and safety. Only one study noted challenges related to doorway and sill height and width during ingress [1]. Meanwhile, only one study included in this review that linked perceptions of driver comfort during ingress and egress with seat selection (stationary versus tilted versus swivelled) [16]. For designers, obtaining the customer "voice" from the very beginning and getting feedback throughout the design process is critical. In later design stages, the voice of the customer is "heard" by engineers as metrics, which are used in design decision making to evaluate and weigh the impact of a decision. For example, General Motors has developed metrics in the domain of visibility to help designers evaluate the impact of their decisions on driver visibility of road and traffic conditions [24]. These subjective metrics can reflect customer satisfaction rather than relying solely on objective measures. Subsequently, a specific design variable (i.e. sill width) can be modelled onto customer satisfaction and captured as a loss function. Loss functions can allow engineers to assess the value of changing a design variable by considering both customer satisfaction and safety. Loss functions can then be derived in future studies of vehicle ingress and egress to determine whether changes to certain features in fact link to improvements in customer satisfaction.

Differences were found with regard to the type of ingress and egress strategies employed (i.e., one foot out vs. two foot out) suggesting a two-leg out strategy was more prominent among older people in their sample, although not all employed this strategy across all vehicle models [7]. However, other studies did not find a specific ingress and egress strategy by sample composition (i.e., young and healthy versus elderly versus pathological) or by vehicle geometry [19,22].

Individuals whom are taller may have more difficulties than persons of shorter stature during ingress (collision with the sill) [9] although the role of roof height is not as important as the distance between the steering wheel and seat [8,9]. Additionally, use and placement of hands, such as grasping the steering wheel, may be an additional means of stability during egress [1]. Although video was used to record hand placements in one particular study [1], specific forces were not measured. Further research is needed to identify where and how hands are placed during both ingress and egress. Studies should also consider tracking and measuring the force of contact between the hand and steering wheel. As well, the door angle should also be considered in vehicle design to determine the optimal vehicle ingress and egress points that are associated with level of comfort.

Eight studies constructed a vehicle mock-up to test ingress and egress [1,7-9,16,18,19,22]. While the mock-up can be used as a proxy measure, none of these studies included a full layout of an actual vehicle. Validation of the vehicle mock-up with actual vehicles is critical to ensure the fidelity of an experimental set-up. A high fidelity mock-up is an important consideration where the influence of specific vehicle dimensions on ingress and egress patterns will be examined in future studies. Additionally, only five of the nine studies used an H-point machine [1,7-9,16]. Future studies should consider including an H-point machine for identification of a vehicle's occupant hip joint centre, as this point can serve as a starting position for many design-related decisions.

The included studies were also limited by the small and homogeneous sample sizes. Additionally, only two of the nine studies included participants with mobility related problems [19,22]. Given the shift towards an older demographic of drivers, more studies with larger samples of healthy and disabled elderly participants (including those using mobility aids) are required to ascertain a better understanding of ingress and egress movement patterns, especially persons with mobility and functional difficulties. Older adults are becoming the largest segment of car buyers in the marketplace, and the health-related changes associated with the aging process means they are more likely to experience challenges that can impact vehicle usability. Hence, improving vehicle design (i.e., making ingress and egress easier) along with comfort ratings, while reducing fall risk for the aging population, has become a focus for many automobile manufacturers [25], particularly as many older users of vehicles report challenges with ingress and egress [5,6]. Seniors have been suggested as the ideal test group when it comes to the development of automotive designs due, in part, to their extensive driving experience; comfort level with technology; health and age-related changes that affect their safety when using a car [26].

To date, no study has examined the association between vehicle design features, personal characteristics and fall risk (including adaptations and perturbations), nor has any study included a representative sample of young and old drivers. Moreover, further investigations are required that capture basic demographic information of the driver population (i.e., age, anthropometry, height, weight) with respect to car selection and performance on ingress and egress strategies. Comparison of gender differences are also warranted as most studies have only included women who were short and men who were tall (i.e. 1,8,9). As men and women have different levels of strength and endurance, as well as anthropometry, further investigations are needed to examine differences in ingress and egress strategies, as well as comfort ratings on various vehicle features.

Further studies are needed that incorporate various populations in the testing of vehicle design features including seat position with respect to the steering wheel, sill width, sill and roof height. Such studies will inform the design of such features based on the minimum and maximum thresholds for vehicle safety and comfort (i.e. reducing fall risk). However, many changes in orientation could prolong the amount of time required from participants. For example, the duration of an experiment in one study lasted approximately 4.5 hours which may have resulted in different ingress and egress strategies due to participant fatigue [8]. Separating aspects of the testing protocol to ensure participants are not fatigued (i.e. two different days) may further improve the validity of study findings. Additionally, a motorised system, instead of manual adjustments by the experimenter, would be preferred to make alterations of vehicle design features on the mock-up [8] although this may be costly to implement.

In conclusion, this review has summarized the primary findings and provided directions for future research. There is great potential to perform research in a new and growing field, as well as an understudied market (i.e. older drivers) that can inform vehicle design changes that enhance mobility and desirability of certain automobiles.

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