

Hand Positions and Forces During Truck Ingress

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Many truck drivers are injured each year due to falls while getting into and out of their vehicles. Design guidelines for steps and handholds are not based on biomechanical data and do not reflect a systems approach to design. As part of a broader effort to improve ingress/egress safety, a laboratory study was conducted to quantify driver postures and motions for a wide range of step and handhold configurations. Data from thirty men and women with a wide range of body size were analyzed to determine the location of the right hand and the force exerted on the aft handhold during the initial phase of ingress. Drivers grasped the external handhold at between 90 and 110 percent of stature above the ground. Peak hand forces averaged 25 percent of body weight, although heavier drivers did not exert significantly more force. Handhold position affected hand force only when the lower step was relatively far from the handhold.

INTRODUCTION

Truck driving is among the most dangerous occupations in which large numbers of U.S. workers are employed. In addition to injuries due to vehicle crashes, truck drivers experience both acute and chronic injuries due to slips and falls on and around their vehicles. Data from a survey of over two dozen U.S. trucking companies found that more than 25% of injuries, and over 80% of injuries resulting in lost work days, resulted from slips and falls (Lin and Cohen 2007). More than 25% of the slip and fall injuries occurred while workers were getting into, onto, out of, or off of vehicles. Jones and Switzer-McIntyre (2003), using data from Ontario, Canada, found that 24% of falls from non-moving vehicles resulted from a slip or trip on a step or fuel tank, which is often used as a step.

Tractor-trailer cabs in the U.S. differ widely in their step and handhold configurations. Most U.S. tractors are so-called conventional cabs in which the engine lies under a hood extending in front of the driver. In the cab-over-engine (COE) configuration, the cab has a flat front and the driver sits above the level of the engine. COE tractors are now uncommon in the U.S., but are the only type of cab for which Federal regulations on ingress/egress systems apply. Federal Motor Carrier Safety Administration (FMCSA) Regulation 399 Subpart L includes a variety of requirements for step and handhold dimensions. Unlike other standards, FMCSA 399 specifies that forces exerted on handrails during ingress and egress should not exceed 35% of body weight. However, the regulation does not specify a test procedure for determining compliance.

The current research is part of a multiphase investigation of truck driver ingress/egress in conventional tractor cabs that includes field and lab studies. As part of the laboratory work, experienced truck drivers entered and exited a vehicle mockup with a range of step and handhold configurations. This paper presents an analysis of the hand positions and hand forces exerted by drivers during ingress. The goal is to answer two questions:

1. What range of vertical handhold locations do drivers use when entering the cab?
2. Are hand forces during ingress affected by the step and handhold configuration?

METHODS

Figure 1 shows the reconfigurable laboratory truck mockup used in this research. The steps can be adjusted vertically and horizontally, simulating the range of step configurations measured in the current truck fleet. Force plates and load cells on the ground, steps, seat, steering wheel, and handholds measured reaction forces. Participants' motions were recorded using a 13-camera VICON passive optical motion capture system.

Testing was conducted with both internal and external handholds at the rear of the door opening. Internal handholds lie within the cab enclosure and are exposed when the door is opened. External handholds are typically vertical bars attached to the outside of the vehicle immediately rearward of the door. Cab dimensions for the mockup were chosen based on an analysis of dimensional data from 30 trucks. The bottom of the door opening (cab floor) was fixed at 1213 mm above the ground. The internal handhold was located 45 mm inside the door opening, 100 mm forward of the rear of the opening, and extended from 1358 to 1794 mm above the ground surface (total usable length of 436 mm). The external handhold was located 113 mm outboard of the sill, 130 mm aft of the door opening, and extended from 1273 to 2207 mm above the ground (total length of 934 mm). A diagonal handhold extended inward and upward from the lower, outboard edge of the simulated door. The door was constructed with an open aluminum frame and was fixed at a 45-degree angle to the fore-aft axis of the mockup for testing.

Table 1 summarizes the characteristics of the subjects whose data were used for the current analysis. Five women and 24 men were tested. The drivers were ages 22 to 65, median 49 years. All had at least five years of truck driving experience.

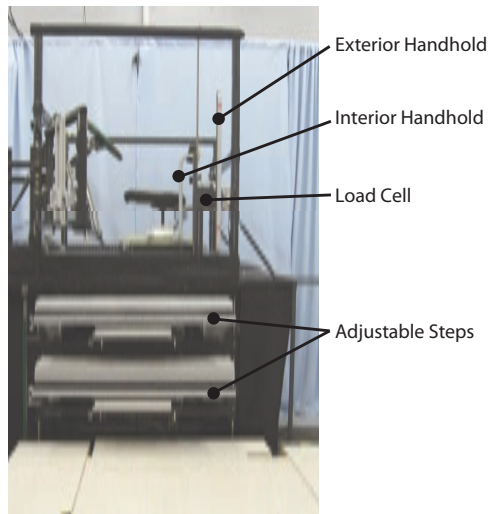


Figure 1. Laboratory mockup with features used for the current analysis labeled.

Table 1
Driver Characteristics

Dimension	Min	Median	Max
Stature (mm)	1554	1761	1902
Body Weight (kg)	68	92	179
Body Mass Index (kg/m ²)	21.5	30.3	49.5

Test Conditions

Drivers entered and exited the cab twice with each combination of the two aft handhold configurations (internal and external) and eight step conditions, for a total of 32 trials per subject. Figure 2 shows the step conditions, which were selected to span a large percentage of the step layouts on tractor cabs in the U.S. The step and sill heights were fixed; step conditions were obtained by varying the lateral position and width of the steps. In all trials, participants were able to use a handhold on the door and to use the steering wheel as a handhold.

Dependent Measures

Two dependent measures were computed for the current analysis. The resultant right-hand force magnitude was computed from the three orthogonal reaction force components measured on the external handhold. The analyses in this paper are based on the first force peak after the second foot left the ground, i.e., when the total ground reaction force went to zero. The right-hand palm center location was calculated from optical markers on the back of the hand. Hand position during this phase of the ingress event was quantified by the height of the palm center above the ground.

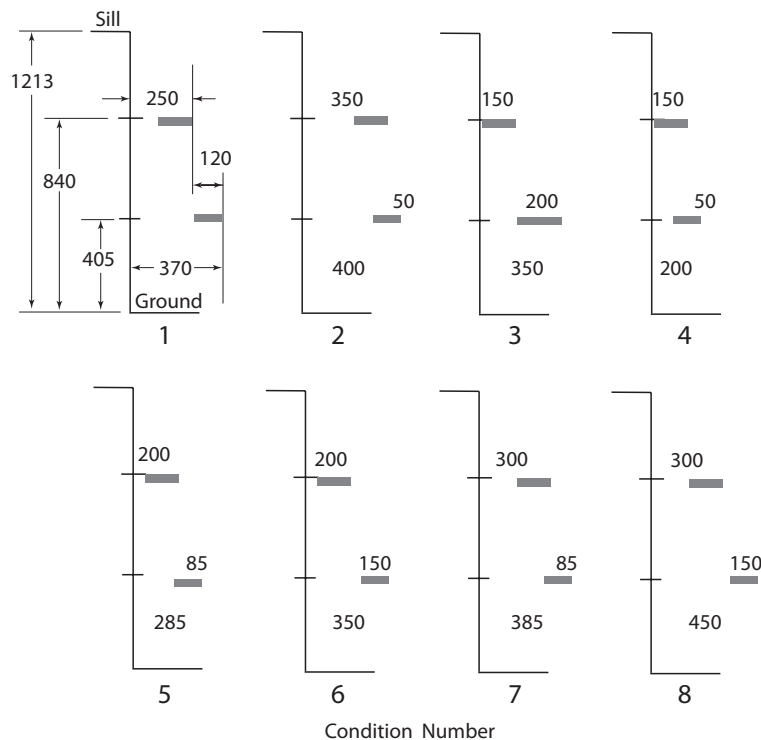


Figure 2. Step conditions (mm).

RESULTS

Right Hand Position

Grasp height above the ground on the external handhold was approximately normally distributed with a mean (standard deviation) of 1720 (114) mm. Figure 3 shows the within-subject mean and stature deviation of grasp height as a function of driver stature for trials with the external handhold. A linear regression analysis on subject means showed that mean grasp height was significantly but weakly related to stature ($674 + 0.599 \text{ Stature}$, $p < 0.01$, $R^2 = 0.31$, $\text{RMSE} = 72 \text{ mm}$). The mean within-subject grasp height was equal to 99 percent of stature (s.d. 4% of stature). For all subjects, the mean grasp height on the external handle was between 90% and 110% of stature.

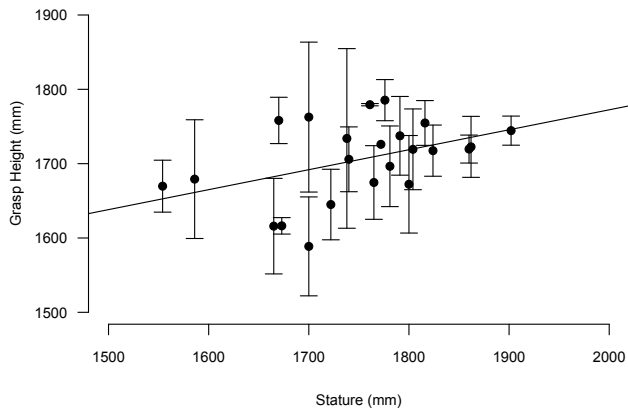


Figure 3. Right hand grasp height on the external handhold above ground (mean \pm 1 sd) by driver stature (mm) across step conditions. Regression on subject means is significant with $p < 0.01$.

For the internal handle, the mean grasp height was 1705 (79) mm. The stature relationship was not significant ($p > 0.01$), probably because of the restriction in the range of the dependent measure imposed by the relatively short handle.

Right Hand Force

Resultant handhold force was not significantly related to body weight, stature, or BMI within or across step conditions. The small number of female subjects precluded an investigation of gender effects. The overall average hand force was 233 (67) N, or 25 (7) percent of body weight. An interaction was observed between resultant force magnitude and step condition. Figure 4 shows means and standard errors for handhold forces by step condition. For all step conditions, the mean external handhold force is larger than the mean internal handhold force. A paired t-test by step condition showed that the mean external handhold force was larger than the internal handhold force ($p < 0.01$) for step conditions 1, 2, 7, and 8. Figure 5 demonstrates that the significant differences occurred for step conditions in which the lower step was farthest from the handhold. In step conditions with a large lateral extent

(lower step $> 350 \text{ mm}$ outboard of the door sill; see Figure 2), the mean hand force magnitude with the external handhold was an average of 37 N (18%) higher than with the internal handhold.

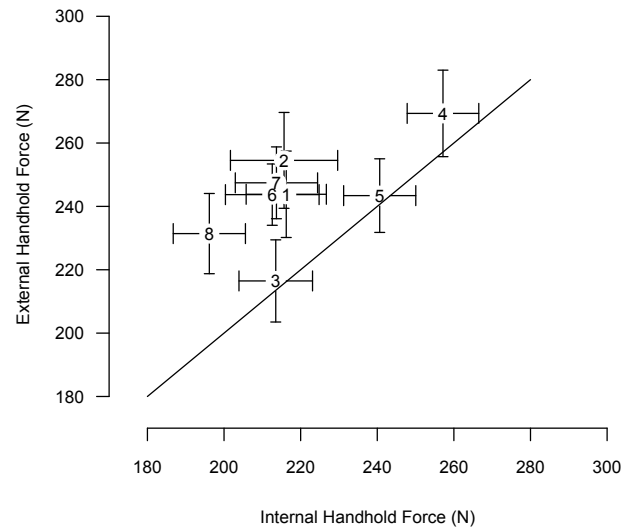


Figure 4. Means and standard errors of internal and external handhold force magnitude by step condition.

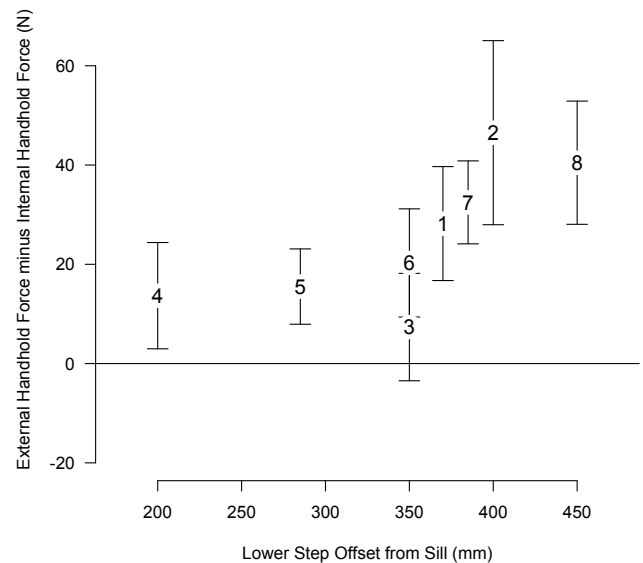


Figure 5. Difference between resultant force magnitudes on internal and external handholds by step condition and the horizontal offset from the sill to the lower step. Step condition numbers (see Figure 2) are plotted at the mean value (N). Mean differences are significantly different from zero ($p < 0.01$) for conditions 1, 2, 7, and 8.

DISCUSSION

The lower end of the needed range of aft handhold locations is determined by ingress requirements. The current findings indicate that drivers place their hands on a vertical handle between 90 and 110% of their stature when entering a truck. Applying the lower value indicates that a handle extending down to about 1370 mm above the ground is needed to accommodate women near the 5th percentile for US stature. These data provide useful guidance for ingress analyses based on human figure models. Postures in which the grasp point is higher than 110% of stature are unlikely to be those that would be chosen by drivers.

The average force exerted on the aft handle as the driver left the ground was 25 percent of body weight, less than the limit of 35 percent of body weight established in FMCSA 399 for cab-over-engine trucks. In the current study, hand force exceeded 35 percent of body weight in 81 trials, indicating that the 35 percent criterion may be unrealistically low.

Unexpectedly, hand force magnitude was not significantly related to body weight. The lack of relationship appears to be due to the wide variance in ingress tactics. Some of the heavier drivers used slower motions, reducing the inertial component of the hand force, and drivers differed in load sharing among the limbs. This result suggests that an improved understanding of ingress tactics is needed, since analyses based on an assumption of uniform tactics would generate increased hand force with body weight, an assumption that these data suggest is unrealistic.

The step configuration, particularly the lateral offset between the lower step and the handhold, was shown to significantly affect hand force. When the step was further outboard, the difference in mean hand force between the external and internal handholds increased, although these conditions were not associated overall with high external handhold forces or low internal handhold forces. One hypothesis is that the wider spacing allows a broader range of postures, so that the handle position effects are magnified.

These results are limited by the relatively small subject pool, although wide ranges of body size and age are represented. Data from only five women were analyzed, which precluded an effort to differentiate gender from associated body size effects. The analyses were conducted using data from one instant during the ingress motion. The biomechanical importance of this instant, when the driver left the ground, may differ depending on tactics. In many trials, the right-hand force was at a maximum at this instant, but in other trials higher forces were observed during transitions between steps. More detailed analyses are needed to characterize hand force trends across tactics and step and handhold configurations and to assess the significance of these trends for driver safety.

ACKNOWLEDGMENTS

This research was supported in part by grant number 1-R01-OH009153-01 from the Centers for Disease Control and Prevention – National Institute for Occupational Safety and

Health. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of NIOSH.

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