AN INVESTIGATION INTO THE OCCURRENCE OF ACCELERATOR/BRAKE PEDAL ACTUATION ERRORS DURING SIMULATED DRIVING

by

Steven B. Rogers

Thesis submitted to the Faculty of
the Virginia Polytechnic Institute and State University
in partial fulfillment for the degree of

MASTER OF SCIENCE

in

Industrial Engineering and Operations Research

APPROVED:

Dr. Walter W. Wierwille, Chairman

Dr. John G. Casali

Dr. Robert D. Dryden

February, 1987
Blacksburg, Virginia

AN INVESTIGATION INTO THE OCCURRENCE OF ACCELERATOR/BRAKE PEDAL ACTUATION ERRORS DURING SIMULATED DRIVING

by

Steven Brian Rogers

Committee Chairman: Dr. Walter W. Wierwille

Industrial Engineering and Operations Research

(ABSTRACT)

Although many studies have investigated accelerator/brake pedal placement in terms of the time needed to move the foot from the accelerator to the brake during emergency braking (i.e. movement time), none have as yet specifically addressed the issue of pedal actuation errors. The primary purpose of the present study was to determine what types of errors (if any) occur, to document the frequency with which various categories of error occur, and to determine whether the different types of error are configuration-dependent.

To accomplish this, the foot movements of subjects were observed and recorded while they performed a variety of driving tasks in an automobile simulator. Subjects drove the simulator on four separate occasions. For each session the simulator was modified to represent one of four different pedal, floor, and seating geometries present in actual automobiles.

Two independent variables were of interest: 1) configuration (as defined by the four pedal arrangements) and 2) vehicle velocity (with velocities above and below 20 m.p.h. representing "highway" and "suburban" speeds respectively). The dependent measures collected included the number and types of errors observed, as well as the movement time required for each configuration.

The data indicate that a variety of errors can be expected, the frequency of which varies greatly with the severity of the error. While the data fail to find any configuration differences with regard to serious errors, the frequencies of "catch" errors below 20 m.p.h. and "scuff" errors were found to be configuration-dependent. Three of the four configurations used demonstrated problems with particular subsets of error.

ACKNOWLEDGEMENTS

My sincere thanks go to Dr. Walter W. Wierwille, without whose technical expertise, guidance, encouragement, patience and support, this thesis would not have been possible. I would also like to thank Dr. John G. Casali and Dr. Robert D. Dryden for their useful advice and encouragement.

My thanks are also extended to for her invaluable help in collecting the data for this experiment.

A great debt is owed to the Statistical Counseling Services at Virginia Tech, and especially Dr. Walter R. Pirie for his input and valuable suggestions. Also, a note of thanks are extended to and for their helpful insights.

Finally, my deep heart-felt thanks to my wife, for her love, patience, and prayerful support during this long process, and also to my parents and sister, for their unending love and encouragement.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd.)

TABLE OF CONTENTS (Cont'd.)

LIST OF TABLES

LIST OF TABLES (Cont'd.)

LIST OF FIGURES

INTRODUCTION

In many situations, the deviation of a movement's endpoint from that which was originally intended may be relatively inconsequential (e.g. resulting in a baseball player hitting a ground ball as opposed to a base hit). The consequences of inaccurate movements in other situations, however, may be much more serious. This is especially true concerning the operation of foot controls in an automobile.

There are a number of errors which could possibly result from movement inaccuracies in this situation. The driver might: 1) inadvertantly actuate the accelerator while attempting to operate the brake, 2) inadvertantly actuate the brake, while intending to operate the accelerator, 3) miss the brake entirely, 4) actuate both the accelerator and the brake pedal during the same movement, or 5) "catch" his or her foot under the brake pedal while attempting to brake.

Each of these errors presents a potential threat of accident. While the threat is obvious for errors in which the driver activates the accelerator instead of the brake or misses the brake entirely, it may not be so obvious for the "catch" errors, which may only result in a small delay before the foot finally reaches the brake. However, as Davies and Watts (1969) have pointed out even a delay as seemingly insignificant as 0.1 second could result in increases in stopping distance of up to 14 ft. (4.27m) at highway speeds (p. 407). It seems reasonable, therefore, to regard even these "insignificant" errors as potential threats to the safety of the driver.

While nothing can be done from a design standpoint to ensure that in a given situation the driver will not make the wrong response choice (i.e. an error in response selection), it _is_ likely that various design parameters will influence the degree to which errors occur during the _execution_ of each response. This is most apparent for errors in which the driver depresses both pedals during the same movement. Here, the horizontal distance separating the two pedals would be a critical factor.

As will be seen from a review of the literature on movement accuracy, the amplitude of a movement plays an important part in determining movement variability. This being true, it would appear that the placement of an automobile's accelerator and brake pedals should be of concern to the designer, since the placement of these controls will largely determine the extent of movement and thus the amount of movement variability and ultimately, the types and number of pedal actuation errors that occur.

LITERATURE REVIEW

Much of the research investigating the use of automobile accelerator and brake pedals has focused on the time needed to move the foot from the accelerator to the brake. Several of the authors of this research have alluded to the possibility of pedal actuation errors and to the importance of their investigation. Glass and Suggs (1977), for example, note that in several instances the movement times of their subjects had to be disregarded because subjects had caught their foot on the brake pedal, and Snyder (1976) suggests that the probabilities of both errors of omission (wherein the driver misses a pedal entirely) and errors of commission (wherein the wrong pedal is actuated) need to be considered by the designer.

Unfortunately, there is nothing in the literature which pertains directly to this issue. Therefore, the following literature review will take a broader approach, examining the literature on movement inaccuracy. At issue in this thesis is the placement of the accelerator and brake pedal controls; therefore, major attention will be devoted to the effects of movement amplitude on accuracy. Because movement error should not be the only concern of the designer, however, the literature on the effects of pedal placement on movement time will also be presented as well as various pedal design guidelines.

Effects of Amplitude on Movement Accuracy

Movement inaccuracies have long been the subject of scientific interest (e.g. Fullerton and Cattell, 1892; Woodworth, 1899). The focus of most of this work has been on the relationship that exists between the average velocity of a movement (i.e. movement amplitude/movement time) and movement accuracy. The fruit of these efforts has been a number of descriptions of what has become known as the "speed-accuracy trade-off", in which the accuracy of a movement decreases as the average movement velocity increases. This relationship has been explained by various authors in terms of the limited information-processing capability of the human operator (Fitts, 1954; Fitts and Peterson, 1964), motor output variability (Schmidt, Zelaznik, and Frank, 1978; Schmidt, Zelaznik, Hawkins, Frank, and Quinn, 1979), the number of closed-loop corrections made during the movement based on either kinaesthetic (Crossman and Goodeve, 1963) or visual feedback (Keele, 1968), and the position of the limb relative to the target at the time of the last visually-based correction (Howarth, Beggs, and Bowden, 1971).

Throughout this literature two indices of movement error have typically been employed and will be referred to during the following discussion. Constant error (CE) refers to the mean of the distribution of movement endpoints about the target (this has also been termed "average error" by some authors) and variable error (VE) refers to the average deviation of these endpoints about that mean (i.e. the within-subject variability or standard deviation of movement endpoints). Of these two dependent measures the former tends to be rather small in magnitude and, therefore, with exception to the earlier studies of Fullerton and Cattell (1892) and Woodworth (1899) often is not reported.

These errors are typically measured along one of two dimensions. Movement error may be measured along an axis parallel to the direction of movement; in this instance, the deviations in movement are referred to as errors of stopping. Should the measurement of error take place along an axis perpendicular to the primary direction of movement, the errors can be regarded as errors in aiming (Howarth and Beggs, 1985). Most of the studies reviewed here focus on errors of stopping; however, the question of errors in aiming has been the primary concern of some authors.

With this background information it now becomes possible to address the empirical studies on movement accuracy. Of the theories proposed to explain the speed-accuracy trade-off, those of Crossman and Goodeve (1963) and Keele (1968) will not be covered in this paper. These theories are merely attempts to explain the speed accuracy relationship as proposed by Fitts (1954) and as such, result in the same empirical formula.

Fullerton and Cattell. One of the earliest studies to demonstrate the effects of amplitude on movement accuracy was actually an investigation into the discriminability of several different movement parameters, including the force and time involved in a movement as well as its extent (Fullerton and Cattell, 1892). To this end, the authors employed several psychophysical methods to determine the range of movement error within which a subject would be unable to detect variations in movement extent. The method of average error was one method used for this purpose. A scale, graduated in millimeters, was fixed along the top edge of a table in front of the subject, who began each trial by placing the index finger of the right hand against an upright at the left end of the scale. During the first of two movements, the subject moved the finger to the right along the scale until it touched a second upright. In this way the amplitude of the movement was established (the subject was unable to see the movement). The second upright was then removed, and an attempt was made to reproduce the extent of the previous movement. Four movement amplitudes were used: 100, 300, 500, and 700 mm. Movement time and inter-movement interval remained constant across amplitudes and were fixed at one second. In general, the results indicated a marked tendency for the subject to overestimate the shorter distances and underestimate the longer movements (the CE was +11.8 mm at 100 mm and -4.8 mm at 700 mm).

There was also an increase in variable error as amplitude increased, ranging from 5.3 to 8.9 mm. Interestingly, the relationship did not obey Weber's Law in that equal increments in amplitude produced decreasing increments in VE at the larger movement distances (Fullerton and Cattell, 1892).

Woodworth. Although preceded by Fullerton and Cattell's (1892) study on movement error, Woodworth's (1899) monograph is regarded as the seminal work in the area. Again, basic movement parameters were the focus of the investigation.

To investigate the effect of amplitude on movement, Woodworth (1899) required his subjects to draw lines a prescribed distance to a "target" line oriented perpendicular to the direction of movement. Movements were made along a straight-edge so that deviations from the target were strictly errors of extent. All movements were made in time with a metronome and were conducted under both visual and non-visual conditions. Four movement distances were studied: 5, 10, 15, and 20 cm. As anticipated, variable error increased as amplitude increased (ranging from 1.07 mm at 5 cm to 2.93 mm at 20 cm). This effect was noted for both the visual and non-visual conditions. Similar to the results of Fullerton and Cattell (1892), Woodworth observed that the effect was non-linear. Increasing movement amplitude had less of an effect on variable error at the larger amplitudes than at smaller distances.

Schmidt, Zelaznik, Frank, Hawkins, and Quinn. Central to the theory proposed by Schmidt et. al. (1978, 1979) is the idea that the variability observed in a movement is the result of variability in the motor processes which produce the movement. Specifically, the theory attempts to pinpoint impulse variability as the source of movement inaccuracy.

Any movement may be separated into an accelerative and decelerative phase, each characterized by a certain amount of force (F) applied over a time (t). The final position of the limb will be a function of these impulses (where impulse = F x t). Any variation in either the force component or the time component of the impulse will result in variation in the movement's endpoint.

The model proposed by Schmidt et. al. (1978, 1979) relies heavily on two basic assumptions: 1) that the variability in force is directly proportional to the amount of force produced, and 2) that the variability in impulse duration is directly proportional to movement time. They base these assumptions on the following empirical results.

Schmidt et. al. (1978) report two experiments in which they examined the relationship between force and force variability. In the first of these experiments they had subjects apply flexion forces of 0.19, 0.38, 0.57, 0.76, 0.95, and .14 kg against an isometric lever with the right hand. The angle at the elbow was 90°. Subjects applied brief bursts of force (approximately 150 msec in duration) with brief 800 msec rests between attempts. The results of the experiment indicated a strong linear relationship between the amount of force produced and the within-subject variability in force ($r = .95$). The procedure used in the second experiment was much the same as in the first except that subjects pressed against a padded plate positioned 25 cm from the elbow and slightly larger loads were used (2.2, 4.3, 6.5, 8.6, 10.8, and 13.9 kg). Here again, the variability in force exhibited a linear relationship with the amount of force produced ($r = .95$). In both experiments, force variability appeared to be directly proportional to the amount of force since the intercept was nearly zero (0.016 kg) (Schmidt et. al., 1978).

Schmidt et. al. (1978) also examined the relationship between movement time and variability in impulse duration. Using a lever similar to that just described, subjects made oscillating flexion and extension movements through angles of 16°, 32°, 48°, and 64°. Four movement times were investigated: 200, 300, 400, and 500 msec. The results showed a strong linear relationship between variability in impulse duration and movement time. Additionally, a near zero intercept of -4 msec appeared to indicate that the variability was directly proportional to movement time (Schmidt et. al., 1978). Using the above findings as a basis for their arguments, Schmidt et. al. (1978, 1979) propose a model to predict the effects of movement amplitude and movement time on accuracy. Although their complete arguments will not be presented here, their conclusions may be summarized as follows.

Increasing amplitude makes it necessary to apply a greater amount of force to the moving limb. This will result in a greater amount of variability in the force applied, which means greater impulse variability, and ultimately an increase in the effective target width, W_e. Decreasing movement time has two opposing effects on variability. Decreasing movement time results in a decreased variability in the time component of the impulse, however, it also means that a greater amount of force must be exerted during the movement, hence an increase in the force component of the impulse. The net effect is to make W_e indirectly proportional to movement time. Combining the effects of amplitude and movement time, Schmidt et. al. (1978, 1979) give the following expression relating the three variables:

$$W_e \propto A \,/\, MT \tag{1}$$

which states that the terminal accuracy of a movement will be directly proportional to the movement's average velocity.

To test their theory, Schmidt et. al. (1978) examined the relationship between W_e and the ratio of A to MT for a simple single-aiming task. Subjects using a hand-held stylus were required to make movements from a starting point to a line target oriented perpendicular to the direction of movement. Four movement times (ranging from 200 to 500 msec) and four movement distances (from 7.5 to 60 cm) were combined to form 16 different A/MT conditions. The subsequent W_e values were measured for each subject. The results indicated a rough linear relationship between A/MT and W_e ($r = .91$). This relationship, however, did not appear to describe the data as well for the lower values of A/MT, leading Schmidt et. al. to speculate that their model may only apply to fast movements (< 200 msec) in which there is not enough time available for within-movement corrections. In this situation movements would be under open-loop, programmed control.

Schmidt et. al. (1979) subsequently decided to test their model using movement times of 140, 170, and 200 msec. Subjects made single aiming movements across distances of 10, 20, and 30 cm to a target. This time their results indicated a strong linear relationship between A/MT and W_e ($r = .97$). Schmidt et. al. conclude that application of their model should be limited to movements short in duration (i.e. < 200 msec); however, they also speculate that their model could apply to longer movements, if those movements are programmed and consequently do not involve within-movement corrections.

To test this hypothesis, Zelaznik, Shapiro, and McColsky (1981) studied the effects of introducing a secondary task during the single aiming movement. Zelaznik et. al. assumed that the addition of an attention-demanding secondary task would result in an insufficient amount of attention being available for within-movement error corrections. Therefore, introduction of the secondary task should have an effect on the relationship between W_e and A/MT for movements long in duration, but should not have an effect on short duration movements in which there is already insufficient time available for error correction.

Zelaznik et. al. used an auditory probe-reaction time task (probe/RT task) as the secondary task in their experiments. This task required the subject to respond as quickly as possible by pressing a key whenever he/she heard a buzzer. In their first experiment, subjects performed 500 msec single aiming movements either with or without the probe/RT task. The results indicated that the W_e / A/MT slope for the 500 msec movement <u>without</u> the probe/RT task was very similar to that previously obtained for movements of comparable duration (Schmidt et. al., 1979) <u>however</u>, the W_e / A/MT slope for the 500 msec movement performed <u>with</u> the probe/RT task was very similar to that observed for <u>300 msec</u> movments in the Schmidt et. al. (1979) study. It would thus appear that the accuracy of a long duration movement can be accounted for by the Schmidt et. al. (1978, 1979) model when attention is occupied by an additional task (Zelaznik et. al., 1981).

The model proposed by Schmidt et. al. (1978, 1979) has not been without its share of criticism. Some of this criticism has centered on the assumptions and mathematics employed by Schmidt et. al. (1979) in modeling their theory (Meyer, Smith and Wright, 1982), while other investigators have taken issue with some of the theory's basic tenets. Attention is now turned to this latter group of studies, since these pose the greatest threat to the theory.

Newell, Carlton, and Hancock (1984) contend that the data presented by Schmidt et. al. (1979) do not demonstrate a linear relationship between W_e and A/MT as Schmidt and his colleagues claim, but rather is indicative of a non-proportional relationship between the two variables. In a re-analysis of the data presented by Schmidt et. al. (1979), Newell et. al. (1984) demonstrate that the coefficient of variation (i.e. W_e/distance) for any given movement time in the Schmidt et. al. study <u>decreases</u> as movement amplitude increases. If the variables were proportional as Schmidt et. al. claim them to be, then the coefficient of variation should remain constant with increasing amplitude. Instead, an increasing, negatively accelerating function is suggested (Newell et. al., 1984). These observations do <u>not</u> mean that a model of movement accuracy based upon impulse variability should be totally discarded. Recent studies on the relationship between force and force variability indicate that just the opposite may be true.

Newell et. al. (1984) noted that many investigators have found force variability to be an increasing, negatively accelerating function of the force produced. This is in stark contrast to the linear relationship adhered to by Schmidt and his colleagues. Newell et. al. suggest that the source of this discrepancy lies in the fact that none of these studies have controlled or measured the time taken by subjects to achieve peak force. Newell and Carlton (1985) obtained estimates of the maximum peak force that could be produced by individual subjects. They then required subjects to produce percentages of their peak force capabilities (ranging from 2.5% to 90% of maximum) in a criterion time to peak force of 200 msec. The resulting force/force variability function was an increasing, negatively accelerating function (Newell and Carlton, 1985). However, Newell and Carlton also discovered that their subjects were not consistent in adhering to the 200 msec criterion time to peak force set by the experimenters, but instead were increasing the time to peak force at the higher percentage force requirements so as to reduce the amount of variability in the force produced. When the actual time to peak force was taken into account, the resulting relationship between force and force variability became a linear function similar to that obtained by Schmidt et. al. (1978). So which function provides the veridical description of impulse variability during movement? The answer appears to be the curvilinear function. Newell, Carlton, and Carlton (1982) found that subjects increase the time to peak force as the average velocity of a movement increases. It is very likely, then, that the relationship between impulse size and impulse variability will be an increasing negatively accelerating function and that a close tie exists between the kinetic and kinematic properties of a movement.

Beggs and Howarth. The theory proposed by Howarth et. al. (1971) to explain the speed-accuracy trade-off in motor behavior is unique on several counts. First, the theory is primarily concerned with _errors of aiming_. It should not, therefore, be viewed as a competitor with those theories that attempt to explain errors parallel to the direction of movement, as these errors may be the result of totally different motor mechanisms (Howarth and Beggs, 1985). Second, the theory proposes that a speed accuracy trade-off will occur only when 1) the movement is under visual control, and 2) the total movement time exceeds that for _one_ visual correction time, t_c. These latter two points will now be addressed.

Howarth and Beggs (1985) maintain that under _non-visual_ conditions, movement accuracy will primarily be a function of movement distance, and movement time will have a relatively small effect. This belief is based on the results of an earlier experiment by Beggs, Andrew, Baker, Dove, Fairclough, and Howarth (1972) in which accuracy of non-visual aiming was examined. These authors contend that the variance observed in the movement's endpoint (measured perpendicular to the direction of movement) will be the sum of two independent sources of variability : 1) variability due to the angular accuracy of aiming and 2) variability due to tremor. Endpoint variability (σ^2) is thus given by

$$\sigma^2 = \sigma_o^2 + (\sigma_\theta D)^2 \tag{2}$$

where σ_o^2= endpoint variance due to tremor

D = total movement distance

and σ_θ = the angular accuracy of aiming.

Beggs et. al. (1972) required subjects to make reaching movements with a pencil from a "home base" to a target. When the subject's hand left the home base, illumination in the room was extinguished and did not return until the subject's hand had reached the target. Five movement distances (10, 20, 30, 40, and 50 cm) and ten movement times (ranging from 350 msec to 1500 msec) were independently manipulated. The results revealed a linear relationship between movement distance and variable error (measured perpendicular to the direction of movement) that accounted for 99.57% of the variance in the data. They found a value for the tremor component of equation 2 equal to 2.7 mm. The angular accuracy of aiming, they determined to be equal to 54' of angle (Beggs et. al., 1972). Movement time did have a slight effect on accuracy. Intermediate speeds were found to be slightly better, in terms of accuracy, than either faster or slower movements with the optimum occuring at about 500 msec (Beggs et. al., 1972).

The theory proposed by Howarth et. al. (1971) to account for a speed accuracy trade-off is based on the occurrence of visually-based corrections during a movement. The model assumes a minimal processing time for visual information, t_c. Thus, the theory maintains that visual samples of movement error are obtained throughout the movement, but that corrections based upon the information obtained from each sample will not be executed until a time equal to t_c has passed. The important point is this: when the time remaining till impact is less than one corrective reaction time (i.e. $< t_c$), the movement over the distance remaining at that time will essentially be uncontrolled. In other words, the remainder of the movement at that time may be characterized as non-visual. As shown by Beggs et. al. (1972) accuracy during a non-visual movement is linearly related to distance, therefore, the aiming accuracy of a visually controlled movement should be linearly related to the distance remaining till impact at the time, t_c (Howarth et. al., 1971). Howarth et. al. (1971) propose the following relationship to account for the error on target

(E):

$$E^2 = E_o{}^2 + (\sigma_\theta d_u)^2 \qquad (3)$$

where E is measured by the root mean square of the
deviations from the target line,
E_o= the error due to tremor
and d_u= the distance remaining to the target at time, t_c.

To test their theory, Howarth et. al. (1971) required a subject to make aiming movements with a pencil from a home position near the right shoulder to a graph paper target (both the home position and the target board were vertically-oriented plates). The movement distance from the tip of the pencil to the target was 50 cm. Movements were made in time with a metronome such that six different movement times were used, ranging from 417 msec to 1428 msec. As the pencil approached the target, an attached cardboard crosspiece broke an infra-red beam positioned at varying distances from the target. This started a timer which stopped the moment the pencil touched the target area. In this way, Howarth and his colleagues were able to graph a series of approach curves relating the time to impact at each of the distances for each of the movement times studied. Once these had been completed it was possible to determine the distance from the target when the time to impact was equal to t_c. The value of t_c used by Howarth et. al. (1971) was 290 msec, a value which Beggs and Howarth (1970) had determined was equal to the corrective reaction time. Fitting a curve to the data (scaled according to movement time) resulted in the following equation:

$$d_u = 814.9\ (t_c/T)^{1.4} \qquad (4)$$

where d_u = distance till impact at time t_c

t_c= visual corrective reaction time (290 msec)

and T = overall movement time.

Substituting this into Equation 2 yielded the following expression relating aiming accuracy to movement time:

$$E^2 = E_o^2 + (814.9)^2\ (\sigma_\theta^2)(t_c/T)^{2.8} \qquad (5)$$

This equation states that movement accuracy should be linearly related to $T^{-2.8}$. Plotting E^2 vs. $T^{-2.8}$, Howarth et. al. (1971) found that indeed the relationship was linear, a straight line providing a very good fit to the data. This finding does lend support to the theory of Howarth et. al. that decreasing movement time in visually-controlled movements serves mainly to increase the distance over which the limb must travel in an uncontrolled manner.

Keele (1981) observed that the model proposed by Howarth et. al. (1971) did not take into account the total movement distance (D). Howarth and Beggs (1985) have subsequently modified their model to include this parameter. The general form is:

$$\sigma_\varepsilon^2 = K^2\sigma_\theta^2 D^2\ (t_c/T)^{2n} + \sigma_t^2 \qquad (6)$$

Effects of amplitude on movement accuracy - summary. In general, increasing the amplitude of a movement has a negative effect on movement accuracy. Both the constant and the variable error of a movement are affected.

Increasing movement amplitude results in a shift in constant error. This shift is characterized by a transition from overshooting the target when small distances are involved to undershooting the target at larger amplitudes (Fullerton and Cattell, 1892). Generally, the constant error tends to be small in magnitude.

The movement literature is consistent in demonstrating an increase in the variable error of a movement with increases in amplitude. Discrepant results have been obtained, however, regarding the shape of this relationship. Data from the early work of Fullerton and Cattell (1892) and Woodworth (1899) indicate that increases in variable error are best described by a negatively accelerating function, while Schmidt et. al. (1978, 1979), in support of their impulse variability model, claim that the relationship is linear. A re-analysis of the data presented by these latter investigators has revealed, however, that the relationship represented by the Schmidt et. al. data is in fact similar to that first found by Fullerton and Cattell (1892) and Woodworth (1899). Thus, it appears that variable error increases at a negatively accelerating rate with equal increments in movement amplitude.

Increasing movement amplitude also results in increases in the variable error of aiming. The work of Beggs et. al. (1971) has shown this to be the result of increasing the distance through which the limb travels in an uncontrolled manner. Thus, for non-visual movements this distance will be equal to the entire movement distance; for visually-controlled movements it will be equal to the distance remaining when the time to impact is equal to one visual corrective reaction time.

Effects of Amplitude on Movement Time

Amplitude may have both an indirect and a direct influence on movement time. As was seen in the previous section, increasing movement amplitude may increase the variability in the movement. If this increased variability causes the driver to catch his or her foot on a pedal, then the result may be an increase in movement time. Increases in movement time in this case will be the indirect result of increases in error. Attention is now turned to the more direct influences of amplitude, i.e. what will be the pure effects of increasing amplitude on movement time outside of those caused by movement error?

Vertical and horizontal positioning of pedals.

Several studies have been directed toward investigating the effects of movement amplitude in the context of the relative positioning of accelerator and brake pedal controls.

Primarily these studies have focused on the effect on introducing a vertical separation between the two pedals. Specifically, this has involved a comparison of configurations where the brake pedal is located higher (closer to the driver) than the accelerator pedal with configurations where the brake pedal is a) located at the same level as the accelerator (coplanar), or b) located at a level somewhat lower (further from the driver) than the accelerator.

Davies and Watts (1969), using male subjects, recorded the movement time (the time required to move the foot from the accelerator to the brake pedal) for two different pedal configurations. The brake pedal in these configurations was located either a) coplanar with the accelerator or b) six inches higher than the accelerator. The two pedals in each configuration were separated by a horizontal distance of four inches and were inclined at an angle of 40° with the baseboard. Subjects were told that the lighting of a red light stimulus in front of them represented an "emergency" situation and that they were to brake as soon as possible upon seeing the light. Davies and Watts found that the mean movement time was significantly less for the coplanar arrangement than for the configuration with the vertical separation between the pedals (0.149 and 0.309 second, respectively). Although the difference in mean movement time was only 0.16 second, the investigators point out that this difference could mean substantial savings in stopping distance at high speeds (Davies and Watts, 1969). In a subsequent study, Davies and Watts (1970) investigated the possibility of generalizing these results to female subjects. In addition to using the same pedal configurations and procedures as in their earlier study (Davies and Watts, 1969) two different seat heights were included (seat height was either 12 or 17 inches). Again, a significant difference in movement time was found for the two configurations. The mean movement time for the coplanar pedals was 0.194 second while that for the "higher brake" arrangement was 0.309 second (Davies and Watts, 1970). Thus it appears that the results obtained for males, i.e. faster coplanar movement times (Davies and Watts, 1969) also apply to the movement times of female subjects. Seat height, however, did not significantly affect movement time (Davies and Watts, 1970).

Snyder (1976) demonstrated the relative contributions of the horizontal and vertical separations to movement time. Movement times were obtained for two coplanar arrangements with horizontal separations of 10.16 cm and 15.24 cm, and a third non-coplanar configuration for which the horizontal and vertical separations were 6.45 and 5.08 cm, respectively. Subjects made foot movements from the accelerator to the brake, as quickly as possible, in response to verbal commands. The non-coplanar arrangement yielded a significantly longer mean movement time (202 msec) than that obtained for either of the coplanar conditions. Interestingly, increasing the horizontal separation from 10.16 cm to 15.24 cm did not result in a significantly longer mean movement time (152 vs. 168 msec, respectively) (Snyder, 1976). Thus, it appears that increases in the vertical component of foot movement from the accelerator to the brake have a much larger effect on movement time than do increases in the horizontal component of the movement.

When the task demands that the driver make simultaneous movements with the left leg, a definite movement time advantage still exists for the coplanar arrangement. Glencross and Anderson (1976) obtained movement times for 1) right leg movements from accelerator to brake, 2) left leg movements from the floor to a clutch and 3) simultaneous movement of both legs to their respective pedals. These movement times were determined for a configuration in which the accelerator, brake, and clutch were coplanar and compared with those obtained when the brake and clutch were located 6 cm higher than the accelerator. Again, subjects were instructed to respond as fast as possible upon seeing a visual neon stimulus. Their results indicated that movement times were faster for the coplanar arrangement of the pedals. "Double leg" movements, however, were typically slower than "single leg" movements (Glencross and Anderson, 1976). Other studies have also demonstrated the superiority of the coplanar arrangement over the "higher" brake pedal configuration (Glass and Suggs, 1977; Sexton and Koppa, 1980).

Several recent studies have sought to determine the effects of locating the brake pedal at a level lower than the accelerator (Glencross and Anderson, 1976; Glass and Suggs, 1977; Morrison, Swope, and Halcomb, 1986). Glencross and Anderson (1976), in a second experiment, located the brake pedal 6 cm below the level of the accelerator. The movement tasks and procedures were identical to those outlined above for their first experiment. They found that the "lower" pedal configuration resulted in longer movement times than those obtained for the coplanar arrangement but that the effect was not as large as that previously noted for the pedal "up" condition of Experiment 1 (Glencross and Anderson, 1976).

Seemingly in contradiction to these findings are those of Glass and Suggs (1977) which suggest that lowering the brake pedal by a small amount may actually reduce movement time. These investigators sought to determine an optimal vertical separation between the accelerator and brake by varying brake pedal height in 25 mm increments, ranging from 102 mm below to 152 mm above the level of the accelerator. They found that the best movement times were obtained when the brake was 25-50 mm lower than the accelerator. The authors attribute this finding to the fact that during actual driving, the slightly lower brake pedal may in fact have a coplanar relationship to the depressed accelerator (Glass and Suggs, 1977).

Most recently, Morrison et. al. (1986) obtained foot movement times while systematically varying the vertical and lateral separations between the pedals. These authors found a statistically significant effect for changes in vertical separation, with coplanar and "lower" brake arrangements (the brake located 5.08 cm below the accelerator) resulting in faster movement times than for those obtained with the brake located 5.08 cm above the accelerator. No differences were found, however, between the coplanar and lower brake arrangements. As in the Snyder (1976) study, changing the lateral separation (in this instance, from 5.08 to 13.34 cm) did not significantly effect movement time.

Although the above studies demonstrate the importance of the horizontal and vertical positioning of the accelerator and brake in determining movement time, a more quantitative description of the effects of amplitude on movement time is desirable. For this, it is necessary to turn once again to yet another description of the speed-accuracy tradeoff in movement behavior.

Fitts. The description of the speed-accuracy trade-off proposed by Fitts (1954) has received more attention than any of the other descriptions yet mentioned. Admittedly, this is partly due to the fact that it has been around longer than the other theories, but a great deal of the attention is due to the fact that it has been able to describe the results of a variety of experiments conducted in a wide range of settings.

Fitts (1954) proposed that the relationship between a movement's speed, accuracy, and amplitude could best be thought of in terms of the limited information processing capabilities of the human motor system (i.e. the maximum amount of information that can be processed in bits/sec is a fixed quantity). Increasing the "information" of a movement, therefore, will mean that a longer time will be required to make the movement.

Fitts (1954) used a term that he called the "index of difficulty" (ID) to define the amount of information inherent in a movement. The index of difficulty for any movement is defined as:

$$ID = \log_2 (A/.5W) \qquad (7)$$

where A = the amplitude of the movement

and W = the width of the target.

Conceptually, the average amplitude (A) in this equation may be thought of as the average signal plus noise (S+N) amplitude and the term ".5W" as representing the peak noise amplitude in the system (Fitts and Peterson, 1964). With the information of a movement defined in this way, the information capacity of the human motor system becomes:

$$C = ID / MT = (\log_2 2A/W) / MT \text{ bits/sec} \qquad (8)$$

Fitts (1954) referred to this quantity as the "binary index of performance" (I_p).

Rather than test the proposed relationship by constraining subjects' movement times and then measuring the distribution of endpoints around a target, Fitts (1954) thought it more expedient to instead constrain the distribution of endpoints (i.e. fix W_e) and determine the resulting effect on movement time. In this form Equation 8 becomes what is generally recognized as Fitt's Law:

$$MT = a + b \log_2 (2A/W) \qquad (9)$$

Note that this equation predicts that the movement time for any two movements will be the same as long as the <u>ratio</u> of movement amplitude to target tolerance is the same for both movements.

Fitts (1954) tested his predictions by requiring subjects to perform a reciprocal tapping task between two targets with a hand-held stylus. Four different target widths (0.25, 0.5, 1, and 2 inches) and four movement amplitudes (2, 4, 8, and 16 inches) were studied. Subjects were instructed to emphasize accuracy rather than speed. Qualitatively, the results agreed with the predictions. Within a given amplitude, increasing target tolerance resulted in decreased movement times. Increasing amplitude (target width constant) resulted in increased movement times. As a quantitative test of his hypothesis, Fitts (1954) calculated the binary index of performance (I_p) for each of the 16 amplitude/target width combinations in his study. This revealed a nearly constant I_p over the range of amplitudes and target widths studied (Fitts, 1954).

Two other experiments reported by Fitts (1954) involving different types of motor tasks lend further support to his hypothesis. The first of these required subjects to transfer washers from one pin to another; the second, involved removing pins from one set of holes and placing them in another set. In each experiment decreasing the amount of acceptable variation in movement or increasing amplitude resulted in increased time to make the movement. The performance rate (I_p) for the washer transfer task varied only 1.3 bits/sec over the eight best conditions, while varying only 1.0 bit/sec over the ten best conditions in the pin transfer task (Fitts, 1954).

The study conducted by Fitts and Peterson (1964) attempted to determine whether the predictions made by Fitt's Law could be extended beyond the cyclical tasks used by Fitts (1954) to discrete movements. Fitts and Peterson required subjects to make single aiming movements to targets either to the left or right of a fixed starting point (this differed from the Fitts (1954) experiment in which the starting point for each movement was determined by the endpoint of the previous movement). Three movement amplitudes (3, 5, and 12 inches) and four target widths (0.125, 0.25, 0.5, and 1 inches) were combined in a factorial fashion. Movement times for each condition were recorded. Again, as was found by Fitts (1954), the predominant factor in determining movement time was the index of movement difficulty (the ID accounted for over 99% of the variance in mean MT). The index of performance found by Fitts and Peterson (1964) was higher than that found by Fitts (1954), however, Fitts and Peterson interpret this as being a result of reaction time being included in the earlier estimate.

More in line with the present application, Drury (1975) attempted to apply Fitts Law to the design of foot pedals. To do this, Drury used a modification of Fitts Law proposed by Welford (1968), being of the form

$$MT = K \times \log_2 (A/W + 1/2) \tag{10}$$

However, Drury proposed that W in this equation be modified to account for the shoe width (S) of the subject. The resulting expression is

$$MT = K \times \log_2 (A / (W+S) + 1/2) \tag{11}$$

To test the validity of Equation 11, Drury (1975) had subjects perform a reciprocal tapping task with the right (preferred) foot between two "pedals". The pedals in this case were actually wooden blocks, 25 mm or 50 mm square, separated by distances ranging from 150 mm to 675 mm. The least-squares line relating the modified ID of Equation 11 to movement time proved to be

$$MT = 0.1874 + 0.0854\,(ID) \qquad (12)$$

The correlation coefficient in this case was 0.970 (Drury, 1975).

Drury claims that Equation 12 can be used (along with a knowledge of the relationship between discrete and reciprocal movement times) to predict the movement times for a variety of pedal configurations. To support his claim, he applied his modified index of difficulty and Equation 12 to the coplanar pedal configuration used by Davies and Watts (1969). This resulted in a predicted movement time of 0.143 second which is very close to that which was actually obtained (0.149 second). Thus, it appears that the equations reported by Drury (1975) may be useful in predicting movement times for configurations in which the accelerator and the brake are coplanar.

Effects of amplitude on movement time - summary. Increasing the amplitude of a movement to a target (error rate held constant) results in an increase in movement time. The time taken to move a given distance to a target of fixed size is well-described for a variety of situations by Fitts Law (Fitts, 1954, Fitts and Peterson, 1964) which states that movement time is linearly related to the "index of difficulty" for the movement. This latter quantity is equal to the logarithm of the ratio of twice the movement amplitude divided by the target width. A modified version of Fitts Law, in which the shoe width of the subject is taken into account, apparently enables the prediction of movement times for a variety of coplanar configurations (Drury, 1975).

In general, the studies investigating the relative positioning of automobile foot pedals have found that a coplanar (Davies and Watts, 1969, 1970; Glencross and Anderson, 1976; Snyder, 1976) or slightly lower brake pedal (Glass and Suggs, 1977) arrangement yield the best movement times. Placing the brake pedal above the level of the accelerator or more than 5 cm below the accelerator (Glass and Suggs, 1977; Glencross and Anderson, 1976) results in substantially longer movement times.

Additional Issues

Distance vs. location cues. The movement involved in transfering the foot from the accelerator to the brake during a braking situation is not a simple one. The situation is complicated by the fact that the vertical separation between the two pedals changes while one is driving. At highway speeds, for example, the accelerator is depressed to a greater extent than would be the case for suburban driving. This variation in each movement's starting point makes distance an unreliable cue upon which to base movement extent. To gain a clearer understanding of this, consider a pedal configuration in which the vertical separation between the accelerator and brake is 4 cm. If at a given moment the driver's foot depresses the accelerator so that the vertical separation between the pedals becomes 6 cm, then any attempt to relocate the brake based on distance information alone, would result in the movement being 2 cm "too short". If, however, the movement were based on information regarding the location of the brake (i.e. location cues) then variation in the starting point of the movement should have little effect on movement accuracy.

Most of the movement literature has shown that the type of cue (distance or location) used to guide a movement will largely be determined by the amplitude of the movement to be reproduced. Gundry (1975) investigated the use of distance and location cues during forearm movements covering 20°, 40°, and 60°. Five groups were used in his study. Two of the groups were given specific instructions to use either distance or location cues in reproducing a 40° movement. The remaining three groups each reproduced one of three movement amplitudes (20°, 40°, or 60°) but were not given any specific instructions as to which movement cue to use. Unknown to the subjects, the experimenter systematically varied the starting point of each reproduction attempt. The effects of starting point variability on constant error was then assessed for each group. The results indicated that neither the location group nor the distance group were totally successful in ignoring either distance or location cues, respectively. <u>However</u>, the effect of starting point manipulation was very small for the location group and had a much larger effect on the constant errors of the distance group. Most interesting were the results for the uninstructed groups. The effect of starting point variability on constant error for the 20° group was not significantly different from that found for the distance group. Likewise, the results for the 60° group were very similar to those found for the location group. Gundry (1975) concludes that distance cues will primarily be used whenever the movement involved is small in amplitude and that location cues will be used when large amplitudes are involved. For movements intermediate in amplitude it appears that a combination of both location and distance cues may be used (Gundry, 1975).

<u>Pedal resistance</u>. Although the amount of force required to activate the acclerator or brake cannot prevent a movement error from occurring, it does serve as a source of feedback as to which pedal the foot is resting on. Ideally then, pedal resistance should enable the driver to discriminate between the two pedals within the range of control movement that does not result in an input to the system. The author knows of no studies which have investigated the discriminability of pedal resistances as they apply to activation of automobile accelerator and brake

pedals. However, a recent study on the discrimination of clutch pedal resistances may provide an indication of what the difference in resistance should be.

To determine the value of the Weber fraction (WF) for clutch pedal resistances, Southall (1985) utilized the psychophysical method of limits. Subjects were required to exert various forces with the left leg against a dynamic foot pedal. "Standard" forces, ranging from 87 to 445 N (i.e. 20 to 100 lbf.) and "comparison" forces (varying in 4.45 N multiples from the standard) were presented to each subject in ascending and descending trials. The subject's task was simply to indicate whether the second force in each standard-comparison pair was greater than, less than, or equal to the first force of the pair. In this way the difference limen (DL) and the point of subjective equality (PSE) was determined for each standard. The results revealed a near constant Weber fraction (ranging from 0.063 to 0.074) with a mean of 0.069. The DL in their experiment varied from 6.54 N for the 89 N standard to 30 N for the 445 N force (Southall, 1985). It should be kept in mind that these results were obtained for forces exerted with the left leg and it is not known whether they hold for forces exerted by the right leg or across different types of pedals (e.g. acclerator vs. brake).

<u>Accelerator and brake pedal design guidelines</u>. Various guidelines have been recommended concerning other aspects of

the automobile's accelerator and brake pedals and will be mentioned briefly here:

1. Chapanis and Kinkade (1972) indicate that brake pedal displacement should be 2-7 inches, while MIL-STD-1472C (1981) gives a range of 1-7 inches.
2. The minimum accelerator displacement should be 1 inch (U.S. Department of Defense, 1981) while the maximum displacement should be about 2 inches (Chapanis and Kinkade, 1972; U.S. Department of Defense, 1981).
3. The angles of the unactuated brake and accelerator pads should be such as to form a 90° angle between the lower leg and the foot when the foot is placed on the pedal (Chapanis and Kinkade, 1972). For ankle-operated pedals such as the automobile accelerator, Hertzberg and Burke (1971) indicate that the pedal angles that produce the greatest mechanical advantage and foot positions of least fatigue are 15 to 35 past the vertical. Outside of this range, mechanical advantage as well as comfort quickly diminish (Hertzberg and Burke, 1971).
4. Chapanis and Kinkade (1972) indicate a minimum resistance of 6 lbs and a maximum resistance of 10 lbs for accelerator pedals. MIL-STD-1472C (1981) lists slightly higher values of 10 lbs and 20 lbs, respectively. These latter values are recommended

by MIL-STD-1472C (1981) for application to designs where the foot rests on the pedal in the unactuated state, and are specifically recommended for application to the design of accelerator pedals (U.S. Department of Defense, 1981). These same values are also suggested by Woodson (1981). The minimum brake pedal resistance should be 10 lbs (Chapanis and Kinkade, 1972).

5. Minimum pedal length and width should be 3.0 and 3.5 inches, respectively, according to Chapanis and Kinkade (1972); MIL-STD-1472C (1981) suggest values of 1 and 3 inches, respectively.
6. Finally, Woodson (1981) suggests that the accelerator be placed 10-15° to the right of the driver's centerline, while the brake pedal should be located directly on the centerline. This latter recommendation is in agreement with the findings of Sexton and Koppa (1980) wherein locating the brake on the centerline produced slightly better movement times than when it was located 8.0 cm to the right of the centerline.

Conclusion

As a preliminary background to the literature on movement accuracy, it was mentioned that errors are typically measured relative to one of two axes. If measured relative to an axis parallel to the direction of movement, these were referred to as errors of stopping or errors of extent. If, instead, measurements were made relative to an axis perpendicular to the direction of movement, they were called errors of aiming. Many of the errors which could possibly occur during the operation of the automobile accelerator and brake pedal can be considered to be a result of one of these two types of error.

Errors that occur during movements from the accelerator to the brake (or from the brake to the accelerator) may be thought of as being the result of errors in stopping. The two classes of errors included here are: 1) "catch" errors, and 2) inadvertant actuation of <u>both</u> pedals.

Movements from the accelerator to a higher brake pedal may be conceptualized as consisting of a vertical and horizontal component (see Figure 1). Should overshooting occur in the horizontal component or undershooting in the vertical component, a catch error will result. In either case, the error can be considered to be an error of <u>extent</u> (i.e. an error in stopping). Given the importance of amplitude (as indicated in the literature) in determining the variable error of movement, it seems that the vertical and horizontal separations between the two pedals could possibly be an important factor in the occurrence of these errors.

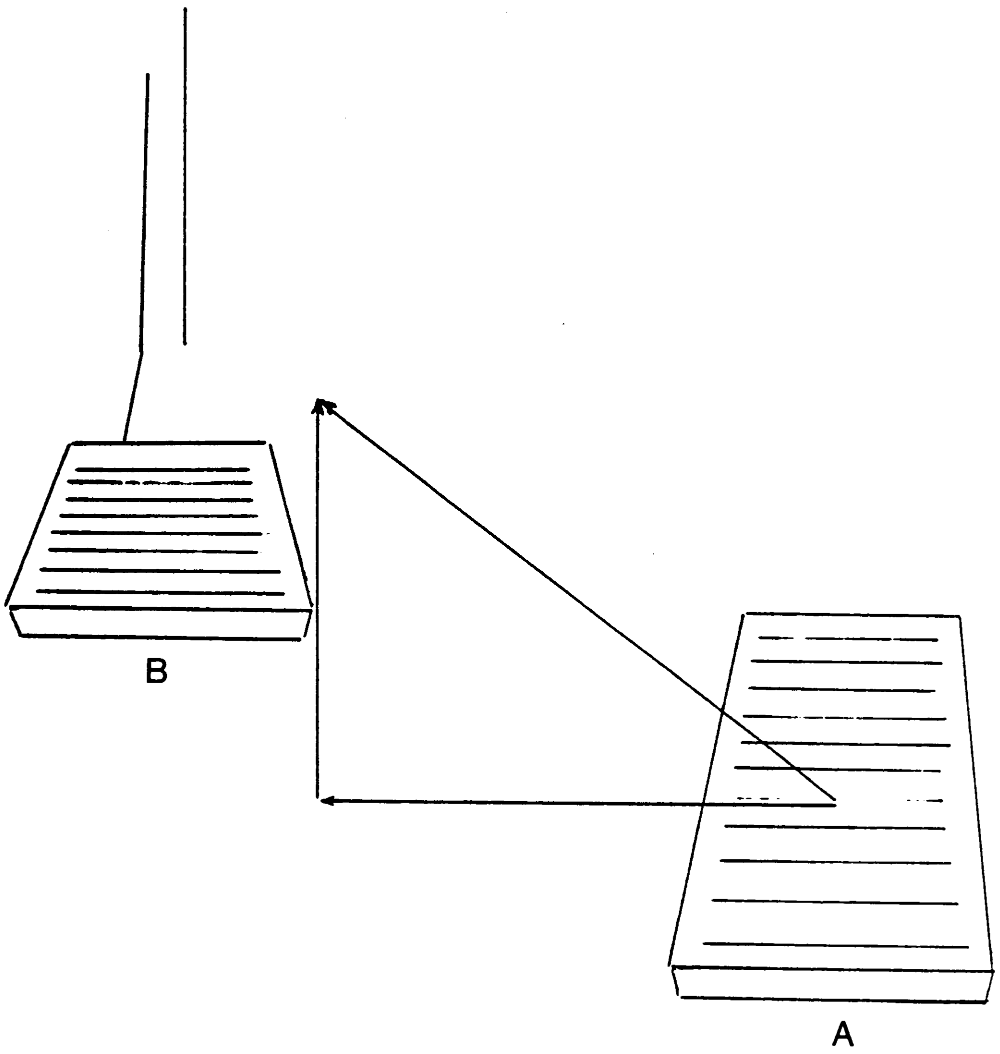

Figure 1: Foot movement from accelerator (A) to brake (B)

If the two pedals are close enough together to allow the shoe to overlap both pedals, then undershooting in the horizontal component of movements between the pedals could result in the depression of both pedals during the same movement. Again, this would be an error of extent. In this instance, the critical concern would be whether the horizontal separation between the two pedals is large enough to allow for lateral variability in the placement of the foot on the pedals without the foot simultaneously depressing both pedals.

Errors occurring during foot movements from a position in front of the pedals to either the accelerator or the brake may be thought of as being the result of errors in aiming (see Figure 2). Two classes of errors may be included here as well: 1) errors in which both pedals are depressed, and 2) errors in which the driver accidently actuates the wrong pedal. (Note that the difference between these two errors is one of degree, the latter being a more extreme case of the former). These errors will be a function of two distances. Of obvious importance is the horizontal separation between the pedals (here again, the horizontal separation should be large enough to allow for lateral variability in the placement of the foot on the pedals). Also important, however, is the distance the foot must travel forward during its movement to the pedals. While driving, the driver's foot movements are under

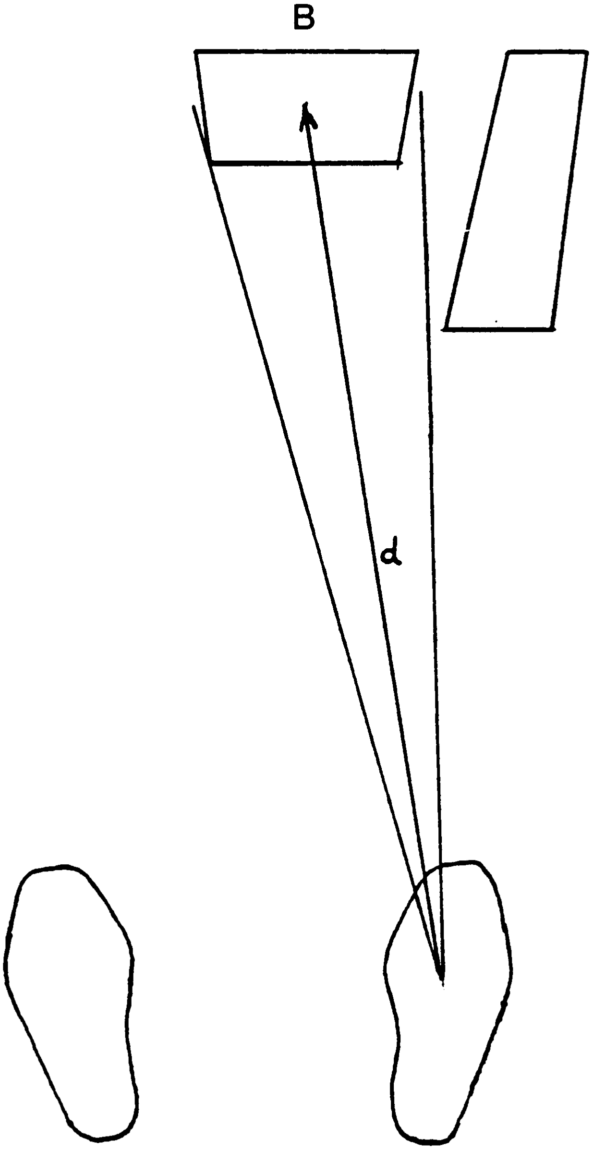

Figure 2: Foot movement from floor to brake (B)

non-visual control (primary attention is focused on the roadway and other vehicles). According to Beggs et. al. (1972) errors of aiming under these conditions will primarily be a function of the distance traversed by the limb (distance d in Figure 2). Unfortunately, this distance will be highly variable, depending on the driver's placement of the foot on the floorboard. Because of this, the primary concern in the occurrence of these errors from the designer's standpoint must be the horizontal separation between the pedals.

An additional class of errors has not yet been considered. These are errors in which the driver's foot catches under one of the pedals during movement from a position in front of the pedals. This type of error will result from undershooting in the vertical component or overshooting in the forward component of the movement and, therefore, may be classified as an error of extent. In this case, the parameter of concern will be the pedal height above the floor.

Besides the possible role that the vertical amplitude of a movement may play in determining movement error, most of the literature indicates that the vertical inter-pedal distance will be a critical factor in determining the movement time from the accelerator to the brake. In addition, the description of the speed-accuracy trade-off proposed by Fitts suggests that the horizontal separation between the pedals (center-to-center) and the width of the brake pedal will also play an important role in determining movement time.

From the above considerations, it is apparent that five design parameters could possibly have an influence on the efficiency with which the driver is able to operate the automobile's accelerator and brake pedals. These are: 1) the horizontal separation between the pedals (i.e. the distance from the left edge of the accelerator to the right edge of the brake), 2) the horizontal (center-to-center) distance from the center of the accelerator to the center of the brake, 3) the vertical separation between the pedals, 4) the vertical height of the pedals above the floor, and 5) the width of the brake pedal.

Purpose

The research presented in this thesis was primarily exploratory in nature and sought to answer a variety of questions. Two of these were descriptive in nature: 1) "What types of pedal actuation errors (if any) occur during driving?", and 2) "How often do the different types of errors occur?".

To answer these questions, the foot movements of subjects "driving" an automobile similator, modified to approximate the pedal, floor, and seating geometries of an actual automobile, were observed. Four such configurations were used and the types and frequencies of error recorded for each.

In the event that a substantial number of errors were found, the experiment would aid in resolving several other questions. These included the following: 3) "Are there differences among the four configurations with regard to the various categories of errors observed?", 4) "If there are differences, <u>which</u> configurations differ?", and 5) "Is the overall pattern of differences in error independent of vehicle velocity, or do the configuration differences in error depend on the speed at which they are observed?".

An additional matter of interest concerned the occurrence of errors in which the subject's foot caught on the brake pedal during movement from the accelerator to the brake. Variation in the initial starting point of these movements occurs because of varying degrees of depression of the accelerator. Of interest was whether or not a significantly greater number of these errors would occur at "highway" velocities than at "residential" speeds. If, in this context, distance cues are being utilized then the number of errors occurring at highway speeds would be expected to be greater than the number occurring at residential speeds. If, instead, location cues are being used, then no differences should be observed.

The final objective of this study was to compare the movement times of the four configurations during an emergency braking situation.

Research Hypotheses

Since no previous research had been conducted in this area, no hypotheses were advanced as to the frequency with which errors might be observed in the experiment. Given that a substantial number of errors did occur, however, several hypotheses were made regarding the distribution of specific types of errors across the four configurations. These were based upon an examination of the pedal dimensions listed in Table 1 (see Methodology section). The hypotheses and the rationale behind them are presented below.

As was stated previously, the horizontal separation between the accelerator and the brake pedal is a critical factor in the occurrence of errors in which the driver actuates the wrong pedal or depresses both pedals during the same movement. The latter can occur only when the horizontal separation between the pedals is less than the shoe width of the driver. Given the mean shoe width of 10.8 cm reported by Damon, Stoudt, and McFarland (1966) and the horizontal separations listed in Table 1, it was evident that the possibility for this type of error existed for all of the configurations included in the present study. It was hypothesized that the greatest number of these errors were likely to occur for Configuration B, since this configuration had the smallest horizontal separation (5.40

cm) and that very few of these errors would be found for Configuration C which had the largest horizontal inter-pedal distance (9.21 cm).

It was also hypothesized that Configurations A and C would have a greater number of catch errors during foot movement from the accelerator to the brake than either Configurations B or D. The literature on movement error indicates that increases in movement amplitude will have a detrimental effect on accuracy, resulting in an increase in the variable error of the movement's endpoint. An examination of the horizontal and vertical inter-pedal distances listed in Table 1 reveals that Configurations A and C had the largest vertical separations (5.08 and 5.40 cm, respectively) and that Configuration C also had the largest horizontal separation. It was hypothesized that these larger amplitudes would result in a greater amount of variability in the vertical and horizontal components of the movement, resulting in a larger number of catch errors for these two configurations during movements from the accelerator to the brake.

It was hypothesized that catch errors that occurred during foot movement from the floor to either the accelerator or the brake would be a function of the pedal's height above the floor, with the pedals farthest above the floor resulting in the greatest numbers of these errors. (Here again, it was thought that the largest amplitudes would result in the greatest amounts of variable error in the vertical component of the movement). It was hypothesized, therefore, that Configurations A and D would have more catches during foot movement from the floor to the pedals than either Configurations B or C. This hypothesis should be viewed with a good deal of caution, however, as certain other factors out of the experimenter's control could have an influence on the occurrence of these errors. For example, although the height of the front edge of the accelerator above the floor was 0 cm for Configuration B and the predicted number of catches in this case would be zero, the subject could have chosen to place his/her foot on the floor <u>between the pedals</u> when instructed to place his/her foot on the floor. In this instance a return movement to the accelerator could result in a catch on the <u>side</u> of the pedal. Unfortunately, the starting point for movements from the floor to the pedals could not be controlled without drawing subjects' attention to their foot movements. The above hypothesis assumed foot movements would be made from a position in front of the pedals.

Configuration C was expected to result in the greatest number of errors occurring during foot movement from the brake to the accelerator. This follows if one considers that during the movement, the foot must "clear" the edge of the brake during its downward path to the accelerator. The wider the brake pedal, the more difficult it becomes to do this without catching the foot on the upper right edge of the brake. Thus, the hypothesis was made that Configuration C with its much wider brake pedal would be likely to result in the greatest number of these errors.

Snyder (1976) demonstrated that increasing the horizontal separation between the accelerator and brake by as much as 5.08 cm (from 10.16 to 15.24 cm) did not result in a significant increase in movement time. Introducing a vertical separation between the pedals, however, did produce a significantly larger mean movement time even when compared with coplanar configurations with larger horizontal inter-pedal distances (Snyder, 1976). Therefore, it was predicted that the major influence on movement time in this study would be the vertical separation between the pedals. In this regard, it was predicted that Configuration D would have the smallest mean movement time, since this was the configuration with the smallest vertical inter-pedal distance. It was further predicted that Configuration C would have the largest movement time due to the dual influence of having the largest vertical separation coupled with the fact that this configuration also had the largest horizontal separation.

METHODOLOGY

Experimental Design

The experimental design used in this study was a 4 x 2 factorial within-subject design. The two factors of interest were pedal configuration and automobile velocity. This design is pictorially represented in Figure 3.

Pedal configuration consisted of four levels. Each level was representative of the pedal, floor, and seating geometry found in an actual automobile (each of these automobiles had power brakes). These various arrangements will simply be referred to as Configurations A, B, C, and D. The horizontal separations (both from the left edge of the accelerator to the right edge of the brake (edge-to-edge) and from the center of the accelerator to the center of the brake (center-to-center)), vertical separation (i.e. the depth separation, normal to the surface of the pedals), pedal height (from the front edge of the pedals to the floor), and brake pedal width associated with each configuration are presented in Table 1. Velocity consisted of two levels, namely speeds above 20 m.p.h. and speeds at or below 20 m.p.h. These two levels were chosen to represent "highway" and "suburban" driving conditions, respectively. Each of the twenty-four subjects who participated in the experiment received all possible combinations of these two variables.

		Configuration			
		A	B	C	D
Velocity	> 20 mph	S1,S2...S24	S1,S2...S24	S1,S2...S24	S1,S2...S24
	≤ 20 mph	S1,S2...S24	S1,S2...S24	S1,S2...S24	S1,S2...S24

Figure 3: Experimental design

TABLE 1

Accelerator and Brake Pedal Dimensions*

	Configuration			
	A	B	C	D
Horizontal separation (edge to edge)	5.72	5.40	9.21	5.72
Horizontal separation (center to center)	13.34	13.02	16.83	13.34
Vertical separation	5.08	3.49	5.40	3.33
Pedal height				
accelerator	16.40	0	12.56	16.40
brake	18.83	13.45	15.03	18.83
Brake pedal width	10.16	10.80	14.29	10.16

*all dimensions are in centimeters

Each subject participated in four data-taking sessions. During each session, dependent measures were gathered for one of the four configurations. To control for order effects, each subject was randomly paired with one of the 24 possible configuration sequences without replacement.

Four different driving scenarios were used in the experiment. Operating within the constraints present during normal driving, the sequencing of commands instructing the subject to drive a given velocity was randomly determined for each of the four scenarios. Thus, the order in which the velocity factor was presented in each scenario was randomly determined.

Each of the 24 possible scenario sequences was randomly assigned to each of the subject/configuration order pairs mentioned above. This method for pairing configurations, scenarios, and subjects was chosen, instead of a Graeco-Latin Square, for the following reasons: 1) with 24 subjects, it was a simple matter to include all possible configuration orders (24) in the study (a Latin-Square alternative would have included only a small subset of this number), 2) similarly, all possible scenario orders (24) could be included easily, 3) a Graeco-Latin Square alternative would have required that exactly the <u>same</u> assumptions be made regarding configuration, scenario, and order factors, i.e. that the three factors do not interact

(Winer, 1971), and perhaps most importantly, 4) the four scenarios used in this study were essentially identical (see Apparatus Section).

The following dependent measures were collected and analyzed:

1) The total number of errors occurring for each configuration.
2) The number of errors occurring during foot movements from:
    a) the accelerator to the brake
    b) the brake to the accelerator
    c) the floor to the brake
    d) the floor to the accelerator
3) The time required for foot movements from the accelerator to the brake during emergency braking.

Subjects

Twenty-four subject volunteers, 12 males and 12 females, participated in this experiment. All were in some way affiliated with Virginia Polytechnic Institute and State University. Each participant was required to have a valid driver's license, to demonstrate at least 20/30 minimum-separable distal visual acuity (with or without correction) as determined by a Landholt C-ring vision test, and to have had no prior experience driving the simulator.

Subjects were paid a flat rate for each session, plus a bonus for completion of all four sessions. Payment for each subject was made upon completion of his/her participation in the experiment.

Apparatus

Driving simulator. The basic apparatus used in this experiment was the moving-base, closed-loop driving simulator located in the Vehicle Analysis and Simulation Laboratory of Virginia Polytechnic Institute and State University. The simulator is capable of receiving control inputs from the driver, processing this information in real time, and providing the driver with the appropriate feedback in the form of visual, motion, audio, and somesthetic (touch or feel related) cues.

Computer control of the simulator is acheived through use of a EAI TR-48 analog computer. The EAI TR-48 has the advantage of being able to solve equations simulating system dynamics in real time and is used, therefore, to control the simulator's motion base. Visual aspects of the simulation are handled by a special-purpose display generation system.

A brief description of each of the simulator's major subsystems follows. For a more detailed description, the reader is referred to Wierwille (1975).

The simulator's motion base is capable of providing four degrees of freedom of movement. These include two translational (longitudinal and lateral) and two angular (roll and yaw) forms of movement. Control inputs from the driver to the steering wheel, the accelerator, and the brake pedal are transformed into electrical analog signals which serve as inputs into various motion equations. The EAI TR-48 analog computer solves these equations in real time and outputs the solutions in the form of electrical signals which serve as inputs to the electrohydraulic servo-actuators attached to the motion platform of the simulator. Electrical feedback to the TR-48 from potentiometers positioned on these actuators complete the closed-loop system. The hydraulic supply for the motion base is contained in a sound-deadened enclosure located behind the motion platform.

Visual feedback is provided via a Tektronics 604 display image produced by the display generation system. This image is converted to EIA television format by a closed-circuit television camera for presentation to the subject on the motion platform. The CCTV image so produced is viewed by the driver through a magnifying (Fresnel) lens which places the image at a distance of approximately 33 feet. The end result is a two-lane roadway having correct perspective. In addition to the dynamic roadway scene, the driver's forward view includes an image of an automobile hood, magnified by the simulator's optical system, to appear full size to the driver.

Audio cues provided to the subject include both engine/drivetrain noise and the sound of rolling tire resistance against the roadway surface. The former is velocity-dependent in amplitude and frequency and emanates from a speaker positioned on the front of the motion platform. The latter is of constant amplitude and emanates from speakers positioned both on the front and the back of the platform.

Various somesthetic cues are provided in the way of vibratory motion of the simulator platform and control "feel". Vibratory motion of the platform is achieved through the use of a DC motor and an eccentric mass. The speed of the motor depends on the simulated velocity, thus making the vibratory frequency velocity-dependent. The simulator's steering system is coupled to a torque motor and active closed-loop force feel system which approximates the power steering of an automobile during highway driving.

Simulator fidelity is further enhanced by the physical appearence of the subject/simulator interface. This interface includes an adjustable bucket seat, a curved plexiglass "windsheild" through which the subject views the visual scene, and a control dash with an illuminated, operational speedometer.

Simulator modifications. For the purposes of the present experiment the interior of the simulator was modified to approximate the interiors of four actual automobiles. The items which were matched for each automobile included:

1) Pedal size, shape, and surface.
2) Pedal location relative to floor, transmission hump, and steering wheel centerline.
3) Pedal location relative to each other.
4) Pedal arc of travel and compliance.
5) Floor contour to the left of the pedals.
6) Transmission hump to right of pedals.
7) Lateral seat position relative to the steering wheel.

In addition to the above physical items, the acceleration characteristic of each vehicle was also approximated.

Foot position/movement time determination. Subjects' foot positions were constantly monitored throughout each session using a low-light level closed-circuit television camera (RCA TC1004U01). By properly orienting a mirror placed above and to the right of the accelerator and brake pedals, it was possible to attach the camera to the side of the simulator in such a way that it remained unobtrusive and unnoticed by the subjects. The video signal from the camera was transmitted simultaneously to a video recorder and a CCTV monitor at the experimenter station. This allowed the experimenters to make on-line observations of each subject's foot movements.

A microphone placed under the simulator's dashboard was also used to detect errors. The audio signal sent from this microphone to headphones allowed the experimenters to hear any contact that was made between the subject's foot and the pedals. This signal was also recorded on the audio channel of the videotape for later review.

An additional degree of redundancy was provided by the potentiometers attached to the accelerator and brake. The analog signals from these sensors were recorded and could be used to detect errors in which the subject accidently depressed both pedals during the same movement or actuated the wrong pedal. These signals, however, remained relatively insensitive to other types of errors in which a pedal was not depressed (e.g. errors in which the subject's foot caught on the brake pedal during movement from the accelerator to the brake). For this reason the video recordings remained the primary source for error detection.

The analog output from these sensors was used, however, to determine foot movement time from the accelerator to the brake during emergency situations. During instances in which the emergency command to brake was given, the return of the acclerator pedal to the null (undepressed) position resulted in a logic "high" signal to a computer. The computer was programmed to begin a count at that moment. Depression of the brake resulted in a logic high signal that stopped the count. In this manner, movement time from the accelerator to the brake was obtained.

Task command/stimulus presentation. The recorded verbal commands comprising each of the scenarios in this study were presented to each subject via a tape recorded message played through a loudspeaker, positioned behind the motion platform slightly to the subject's right.

A visual (red) light stimulus mounted on the center of the dashboard was used to present the emergency "command" to brake. This visual stimulus was chosen to convey an emergency situation rather than a verbal command to emergency brake for two reasons: 1) in most "real world" driving situations the stimuli conveying an emergency will be visual, and 2) the command is sudden and immediate, as are most emergencies.

Driving scenarios. To keep subjects from developing a set pattern of responses and to reduce the effects of subject expectancy, four different scenarios were used in this study. Each scenario required subjects to perform a variety of driving tasks. These tasks may be classified and grouped according to the type of foot movement required for their performance. The tasks and their associated foot movements are presented in Table 2.

Grouping of the tasks in this manner revealed a number of different ways in which the same foot movement could be generated using different driving tasks. Thus, by randomly choosing from among the tasks listed for a given foot

TABLE 2

Driving Tasks and Associated Foot Movements

Foot Movement	Task
Brake to accelerator (B → A)	-with the car in drive, but at a standstill the subject accelerates to a specified velocity.
	-with the car in reverse and at a standstill the subject backs the car.
	-with the car in drive, but at a standstill on the side of the road, the subject pulls onto the road.
	-having used the brakes to slow the car the subject must maintain the lower velocity.
Accelerator to brake (A → B)	-with the car in motion, the subject brings the car to a stop.
	-with the car in motion, the subject performs an emergency stop.
	-with the car in motion the subject uses the brake to slow the car to a lower velocity.

TABLE 2

Driving Tasks and Associated Foot Movements (Cont'd.)

Foot Movement	Task
Accelerator to brake (A → B) (cont'd.)	-with the car in motion, the subject uses the brake to bring the car to a stop on the left or right side of the road.
	-while backing the car the subject must bring the car to a stop.
Floor to brake (F → B)	-with the car in park the subject shifts to drive.
	-with the car in park the subject shifts to reverse.
	-while allowing the car to coast to a lower velocity with both feet on the floor, the subject performs an emergency stop.
Floor to accelerator (F → A)	-the subject, with both feet on the floor, allows the car to coast to a specified velocity and then maintains that velocity.

movement, subject expectancy could be kept at a low level.

Using the information presented in Table 2 it was possible to generate a number of different scenarios that were equivalent with regard to the number and types of foot movements involved. Although the task used to achieve a given foot movement was randomly chosen from Table 2, the order in which the different types of foot movement occurred within each scenario was subject to two constraints as listed below:

1) Beginning each scenario with the car in park and the subject's feet on the floor demanded that the first and second foot movements of each scenario be, respectively, floor to brake (F → B) and brake to accelerator (B → A) movements. This same sequence of foot movements necessarily followed every instance in which the car was in park and the subject's feet were on the floor.
2) Movements between pedals necessarily alternated between brake to accelerator (B → A) and accelerator to brake (A → B) movements.
   Consecutive, identical movements between the two pedals were not possible without intervening foot movements to and from the floor (e.g. an A → B movement could not be immediately followed by another A → B movement).

In addition to performing tasks involving foot movement, subjects were required to perform tasks that did not involve foot movement. These included lane changing, accelerating to a higher velocity, and coasting to a lower velocity (see Table 3).

The remaining constraints concerned the assignment of the different driving tasks to each scenario. These were:

3) Each task listed in Table 2 had to appear an equal number of times across the four scenarios. This restriction did not apply to tasks not involving foot movement to, from, or between pedals (with the exception of lane changes which occurred an equal number of times for each scenario). This number also had to be balanced across both levels of the velocity factor.
4) Each task (except those having to do with backing the car) could have at the maximum two consecutive appearances in the scenario. It was hoped that this would reduce the amount of task expectancy.
5) No scenario could contain two consecutive commands to back the car.
6) The final task had to require the subject to stop the car.

Operating within the above contraints, four scenarios were developed. Each scenario contained 32 B → A movements and 28 A → B movements for a total of 60 foot movements

TABLE 3

Tasks Not Involving Foot Movement Between or to Pedals

- the subject changes lanes.
- with the right foot already on the accelerator, the subject accelerates to a higher velocity.
- the subject allows the car to coast to a lower velocity without removing the right foot from the accelerator.

---

between the two pedals. Additionally, each scenario contained nine movements from the floor to the brake and four movements from the floor to the accelerator.

The reader will note that the number of B → A movements was greater than the number of A → B movements and that the same was true for F → B and F → A movements, respectively. These discrepancies were due to the following. Four times in each scenario the B → A/A → B cycle was replaced by a B → A/A → F/F → B sequence which meant that on these four occasions, a B → A movement was not paired with an A → B movement. Likewise, four times in each scenario the subject made a movement from F to B while the car was in park (the subject was never instructed to place his/her foot on the accelerator to shift out of park).

A sample portion of a scenario may be found in Appendix A. The resulting tally of foot movements per configuration across the entire experiment, categorized according to type of foot movement, is shown in Table 4.

The differences in the number of movements that occurred between the two velocity categories were a result of the following. Regardless of the car's final velocity, accelerating the car from a standstill meant that the first foot movement (B → A) would always be below 20 m.p.h. Thus, although the number of times the instructed velocity was above 20 m.p.h. equalled the number of times it was below 20 m.p.h. for each configuration, the B → A movements that

TABLE 4

Distribution of Foot Movements Among Velocities and Configurations

Foot Movement	Below 20	Above 20	Total Per Configuration	Total Per Experiment (x4)
B → A	672	96	768	3,072
A → B	384	288	672	2,688
F → B	168	48	216	864
F → A	48	48	96	384
Total Per Configuration	1,272	480	1,752	
Total Per Experiment (x4)	5,088	1,920		7,008

occurred as a result of these commands always occurred below 20 m.p.h. Likewise, it was assumed that the B → A and A → B movements that occurred in response to commands to back the car would occur at speeds below 20 m.p.h. (it seemed highly unlikely that a subject would attempt to back the car at speeds above 20 m.p.h.). Because of these constraints it was impossible to balance the number of opportunities for error across the two velocity categories. It is very important to realize that the number of opportunities for error was balanced across configurations, both with regard to the number of different types of foot movement that occurred and the number of movements of each type occurring at each velocity. In other words, any comparison made between configurations would be based on equal opportunity for error. This was not true for comparisons between the two velocity categories.

Of particular interest in the present study was a comparison between the two velocity categories with regard to the number of errors in which the subject's foot caught on the brake during A → B movement. The reader will note from Table 4 that there were 96 additional opportunities for this type of error below 20 m.p.h. than above. This discrepancy is due to an additional 96 A → B movements that occurred in response to commands to back the car. To make this comparison between the two velocity categories meaningful, A → B catches that occurred during reverse were not included in this particular analysis (this was the _only_ comparison in the entire experiment in which some of the relevant data were not employed). Thus, the comparison made was based on equal opportunity for this type of error.

Each scenario was executed on both curved and straight roads. All driving took place in subdued light (simulated twilight) conditions. The pedal area of the simulator appeared dark when compared to the windshield scene. The laboratory lights were off during the simulation. However, there was sufficient light in the floor area to videotape the feet and pedals, since the camera used was a low-light level camera with auto-iris (see section on foot position/movement time determination above).

Procedure

Upon first entering the laboratory, subjects were required to show the experimenter a valid driver's license and were given a Landholt C-ring vision examination. Each subject was required to have at least 20/30 minimum-separable distal visual acuity or better, with or without correction, to ensure that each could correctly interpret the instrumentation and visual stimuli present in the simulation. Subjects thus found to be eligible were then given the instructions and informed consent document shown in Appendix B.

Several anthropometric measurements were taken. These included the height, weight, sitting height, popliteal height, shoe length and shoe width of each subject. Sitting height and popliteal height were determined while the subject was sitting in a hard wooden chair with the subject's back straight and feet flat on the floor. Shoe width was measured at the ball of the foot. This last measurement was of particular interest in this study since shoe width was thought to be a potentially important contributor to inadvertant actuation.

Once in the simulator, the subject was instructed to wear the seat belt at all times during the run and was told to adjust the seat position forward, if so desired, until the seat was in a comfortable position. The initial seat position was at the rearmost detent for all subjects. Each subject then proceeded through the driving scenario as prompted by the recorded verbal commands and visual stimuli.

Subjects were required to return to the laboratory on three additional occasions for a total of four sessions. The first session differed from the remaining three in that the subject was given a short period of time (approximately 10 minutes) to drive the simulator while responding to commands from a scenario similar, but not identical, to those to be used during actual testing. This "warm-up" scenario was identical for all subjects and included each of the tasks listed in Tables 2 and 3. The pedal configuration for this practice session was the same as would be used during the first of the four data-taking sessions. Because pedal configuration was counterbalanced across subjects, practice on the configurations was also equalized across subjects. During the remaining sessions the preliminary tests and measurements mentioned above were not performed, but each subject, upon entering the laboratory, was seated in the simulator, reminded of the basic instructions, and then proceeded to drive the simulator, modified to approximate the appropriate configuration. At the completion of the fourth session, subjects were paid for their participation in the study.

RESULTS

Error Identification and Classification

In total, 297 errors (excluding instructional errors) were observed in this experiment during the 72 hours in which data were taken. This represents an average rate of occurrence of approximately 4 errors per hour of observation, or one error per 24 foot movements made.

A variety of errors was noted. An early attempt at classification of these errors was made during the on-line observation of each subject's foot movements. The main effort of the experimenters at this point, however, was the recording of any error's position on the videotape (for later analysis), and thus these early descriptions were rather crude.

After all the data for the experiment had been collected, two experimenters carefully reviewed each error using the videotapes. This review process involved 1) the incorporation of each error into an existing category or 2) the formation of a new category if it was felt that a particular error was not adequately described by an existing one. By the completion of this phase of classification, there existed a description of each error observed in the experiment as well as a tally as to the number of times each had occurred.

During the final phase of classification the data were separated into three major categories: 1) serious errors,

2) catch errors, and 3) scuff errors. Serious errors included those in which the "wrong" pedal was actuated (i.e. other than that which was intended) or errors in which both pedals were depressed. The catch category included errors where the positioning of the pedals was such as to interfere with foot movement. The scuff error category included many of the errors contained in the catch category except that in this instance interference with foot movement was minimal. Other errors in this last category were viewed as representing a potential for error which should be of concern to the designer. A short description of the errors contained in each of these three categories may be found in Table 5. The reader will note that an additional category is listed at the end of Table 5 that is not mentioned above. Instructional errors included instances where a subject failed to obey instructions to perform a certain task and therefore may be regarded as separate from the "pedal" errors included in the serious, catch, and scuff categories. Distribution of these instructional errors across configurations was expected to provide some indication as to the equivalency of conditions across the four configurations. In other words, if large differences in instructional error rates occurred as a function of configuration, the experiment would be suspect in terms of possible bias.

TABLE 5

Error Classification and Description Based Upon Experimental Results

---

Serious Errors

- Subject mistakes the accelerator for the brake (depresses the accelerator instead of the brake)
- Subject mistakes the brake for the accelerator (depresses the brake instead of the accelerator)
- Subject's foot overlaps or depresses both pedals while depressing the brake
- Subject's foot overlaps or depresses both pedals while depressing the accelerator

Catch Errors

- During movement from the accelerator to the brake, the subject's foot catches on lower right edge of the brake.
- During movement from the brake to the accelerator, the subject's foot catches on the upper right side of the brake.
- During movement from the brake to the accelerator, the subject's foot catches on the lower left edge of the accelerator.
- During movement from the floor to the brake, the subject's foot catches on the lower front edge of brake.

TABLE 5

Error Classification and Description (Cont'd.)

Catch Errors (Cont'd.)

- During movement from the floor to the accelerator, the subject's foot catches on the lower edge of the accelerator.
- During movement from the pedals to the floor, the subject's foot catches on the brake.

Scuff Errors

- During movement from the accelerator to the brake, the subject's foot scuffs the right edge of the brake.
- During movement from the brake to the accelerator, the subject's foot scuffs the upper right edge of the brake.
- During movement from the brake to the accelerator, the subject's foot scuffs the left edge of the accelerator.
- During movement from the floor to the accelerator, the subject's foot scuffs the brake.
- During movement from the floor to the brake, the subject's foot scuffs the accelerator.
- During movement from the pedals to the floor, the subject's foot scuffs the accelerator.
- While letting off of the accelerator, the subject's foot scuffs the brake.

TABLE 5

Error Classification and Description (Cont'd.)

Scuff Errors (Cont'd.)

- During movement from the pedals to the floor, the subject scuffs his/her foot on the brake.
- While depressing the brake, the subject's foot nudges the accelerator pedal to the side.
- While depressing the accelerator, the subject's foot nudges the side of brake.

Instructional Errors

- When requested to place both feet on the floor, the subject keeps foot near the accelerator or moves foot to a position above and between pedals.
- When requested to let off the accelerator, the subject places foot on the floor.
- Other instructional errors.

Main Analyses

To determine whether the parametric assumption of normality could reasonably be made for the error data gathered in the experiment, Stephens modification of the Kolmogorov-Smirnov and Kuiper goodness-of-fit statistics (Stephens, 1974) were used to test the data for any deviations from normality. The results of these tests for the total number of errors per subject (serious, catch, and scuff categories combined), total number of catch errors per subject, and the total number of scuff errors per subject, are shown in Appendix C for each of the configurations. Because of the large number of zero error occurrences in the serious error category (see below), it was not deemed necessary to perform normality tests on the serious error data. With the exception of the total error data for Configurations B and C, the distributions of error for each configuration demonstrated significant deviations from normality. To avoid violating parametric assumptions and for the sake of consistency, nonparametric analyses were used to examine all error data for this experiment. (A desirable goal in the analysis of the error data from a design standpoint, would ultimately be the "pinpointing" of the specific design parameters responsible for the errors which were observed. To accomplish this for an observational study, such as the present experiment, in which there are very few systematic changes between the treatments involved, would require a multiple regression approach to pinpoint the parameters responsible for the greatest amount of variation in the data. The above-mentioned deviations from normality along with several other aspects of the present experiment make suspect any results obtained by these methods. This approach was attempted, however, using the total number of errors per subject for each configuration. The interested reader is directed to Appendix D for the results of these analyses, but is cautioned as to their validity).

Analyses were conducted to obtain answers to the following questions: 1) Are there differences among the four configurations with regard to the total number of errors observed?, 2) Do differences exist among the configurations with regard to each of the error categories (i.e. serious, catch, scuff, and instructional errors)?, 3) If differences are found, which configurations differ?, and finally, 4) What differences exist when each velocity category (i.e. above and below 20 m.p.h.) is examined separately?.

Overall analysis. To test for differences among the four configurations with regard to the total number of errors (serious, catch, and scuff error data combined) that occurred for each configuration, an Aligned Ranks Test (Lehmann, 1975) was performed. A significant difference in total error per configuration was found, $\underline{Q}$ (3) = 17.77, $\underline{p}$

< 0.0005. To determine which of the configurations differed, pair-wise comparisons were performed using the Wilcoxon Signed-Ranks Test (Lehmann, 1975). The results of these analyses are presented in Table 6. For each comparison, difference scores were obtained by subtracting the error scores of the second configuration listed, from those of the first (e.g. for A vs. B, the scores of B were subtracted from A). Zero differences were discarded, and the remaining differences were ranked. (When using this method of dealing with zeros, the comparisons which are made should only be interpreted as representing instances in which the number of errors observed for each configuration were not equal). V_s and V_r represent the sums of the positive and the negative signed ranks, respectively. (This same convention will be used for all following tables in which the results of the Wilcoxon Signed-Ranks Test are presented). The two-sided probability of finding either a V_s or a V_r (whichever was the smaller for that particular comparison) equal to that which was actually found, when the null hypothesis is true, is shown in the final two columns of the table. When performed on the total error data, these analyses reveal that significantly fewer errors occurred for Configuration D than for any of the other configurations. Configuration A also had significantly fewer errors than did B. The results of these tests may be summarized as follows:

TABLE 6

Results of All Possible Pair-Wise Comparisons Using the Wilcoxon Signed-Ranks Test on Total Error Data.

Comparison	N	V_s	V_r	$p\ (V_s \leq v)$	$p\ (V_r \leq v)$
A vs. B	22	53.5	199.5	0.0188	
C	19	78.5	111.5	0.5412	
D	17	153.0	30.0		0.0266
B vs. C	23	191.0	85.0		0.1118
D	22	237.0	16.0		<0.0004
C vs. D	21	199.0	32.0		0.0040

$$\underline{D}\quad \underline{A\quad C}\hspace{-0.8em}\underline{\vphantom{\underline{A}}\hspace{0.8em}\quad B} \qquad\qquad \alpha_e=0.05$$

where configurations with a common underline do not differ significantly.

Examination of the total error per configuration for each velocity category revealed significant differences among the four configurations, both for speeds above 20 m.p.h., $\underline{Q}$ (3) = 14.24, $\underline{p} < 0.0029$, and below 20 m.p.h., $\underline{Q}$ (3) = 22.95, $\underline{p} < 0.0001$.

Pairwise comparisons were then conducted using the Wilcoxon Signed-Ranks Test. At speeds above 20 m.p.h., Configurations A and B were found to have significantly more errors than Configurations C and D (see Table 7 for the results of all pair-wise comparisons). These results may be summarized as follows:

$$\underline{D\quad C}\quad \underline{A\quad B} \qquad\qquad \alpha_e=0.05$$

Below 20 m.p.h. Configuration B and C were found to have a significantly greater number of errors than Configurations A or D. The results of these analyses are presented in Table 8 and are summarized below.

$$\underline{D\quad A}\quad \underline{C\quad B} \qquad\qquad \alpha_e=0.05$$

The total number of error occurrences for each configuration is shown in Figure 4, and the division of this total into errors above and below 20 m.p.h. is shown in Figure 5.

TABLE 7

Results of All Possible Pair-Wise Comparisons Using the Wilcoxon Signed-Ranks Test on Total Number of Errors Occurring Above 20 m.p.h.

Comparison	N	V_s	V_r	p ($V_s \leq v$)	p ($V_r \leq v$)
A vs. B	18	64.5	106.5	0.3928	
C	14	85.0	20.0		0.0418
D	17	131.5	21.5		0.0080
B vs. C	18	146.5	24.5		0.0066
D	16	124.5	11.5		0.0022
C vs. D	13	63.5	27.5		0.2348

TABLE 8

Results of All Possible Pair-Wise Comparisons Using the Wilcoxon Signed-Ranks Test on Total Number of Errors Occurring Below 20 m.p.h.

Comparison	N	V_s	V_r	p ($V_s \leq v$)	p ($V_r \leq v$)
A vs. B	20	11.0	199.0	0.0002	
C	18	31.5	139.5	0.0182	
D	18	111.0	60.0		0.2838
B vs. C	19	119.5	70.5		0.3524
D	21	223.0	8.0		0.0002
C vs. D	19	168.5	21.5		0.0020

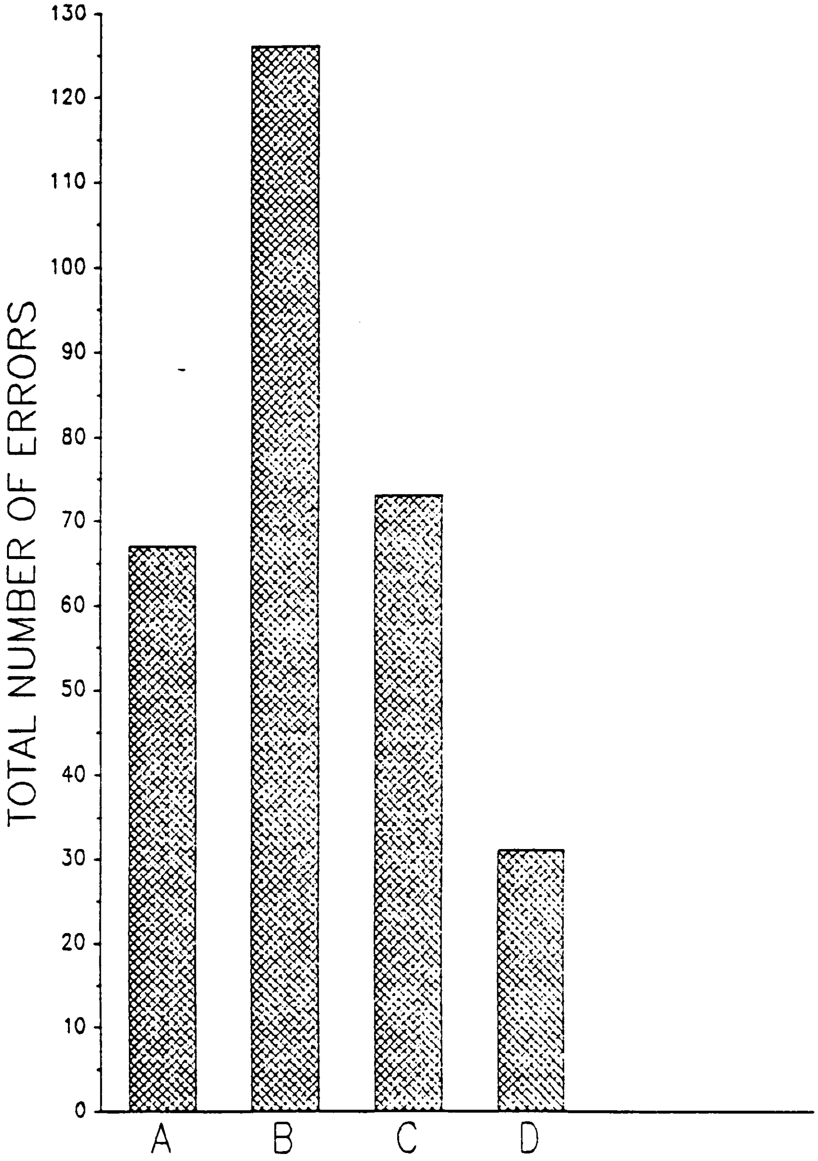

Figure 4: Total number of errors per configuration

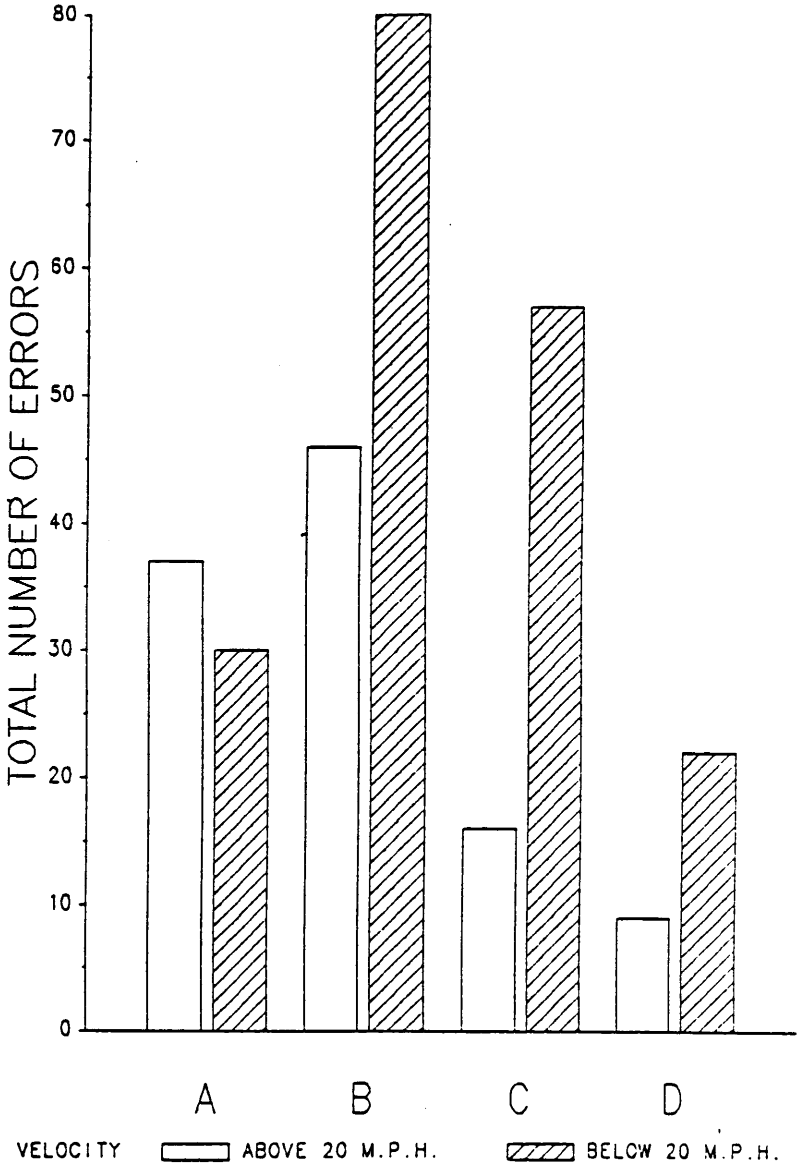

Figure 5: Total number of errors above and below 20 m.p.h. per configuration (number of opportunities for error differ above and below 20 m.p.h. (see Table 4))

Serious errors. Serious errors were very infrequent, occurring only 15 times throughout the entire experiment. This represents an average rate of occurrence of 1 serious error per 4.8 hours of data taken or one error per every 468 foot movements made. Each of the serious errors listed in Table 5 occurred at least once in the study. The distribution of these raw errors across the four configurations is shown in Appendix E.

Unfortunately, there are no nonparametric tests available which are capable of satisfactorily handling such sparse data. The best that can be done in this situation is to apply the Aligned Ranks Test, keeping in mind that the results of such an analysis should be interpreted with extreme caution. With this in mind, an Aligned Ranks Test was performed on the serious error data. The resulting value of Q was not found to be significant, $Q(3) = 2.16$, $p > 0.05$, thus indicating an absence of differences among the four configurations with regard to serious errors.

Because of the extreme sparsity of the serious error data, and the lack of significance for the data summed over velocity, Aligned-Ranks Tests were not performed on the serious errors occurring in each velocity category.

Catch errors. In total, 73 catch errors were observed, occurring at an average rate of one catch error per hour of data taken or one error per every 96 foot movements made. Application of the Aligned Ranks Test to the catch error data revealed the lack of a significant difference among the four configurations in terms of the total number of catches per configuration, $Q = 4.52$, $p > .05$. For the sake of completeness, however, the total raw number of catches observed for each of the configurations is shown in Appendix F along with the raw data for the other major categories of error.

Aligned Ranks Tests were then performed to determine whether differences in the number of catch errors might exist among the four configurations when each of the two velocity categories (i.e. above or below 20 m.p.h.) were examined separately. These analyses revealed no differences among the configurations at speeds above 20 m.p.h., but did indicate a significant difference below 20 m.p.h., $Q\ (3) = 10.62$, $p < 0.014$. Pair-wise comparisons, using the Wilcoxon Signed-Ranks Test, exposed Configuration C as having significantly more errors at lower velocities than either A or D. The results of these analyses are presented in Table 9 and may be summarized as follows:

$$\begin{array}{cccc} \mathrm{A} & \mathrm{D} & \mathrm{B} & \mathrm{C} \\ \cline{1-3} & & & \\[-1.2em] \cline{3-4} \end{array} \qquad \alpha_e = 0.05$$

The total raw number of catch errors occurring above 20 m.p.h. is presented in Appendix F. The total number of catch errors below 20 m.p.h. per configuration is depicted in Figure 6.

<u>Scuff errors</u>. Scuff errors occurred at an average rate of approximately three errors per hour of data taken or one

TABLE 9

Results of All Possible Pair-Wise Comparisons Using the Wilcoxon Signed-Ranks Test on Catch Errors Occurring Below 20 m.p.h.

Comparison	N	V_s	V_r	$p\ (V_s \leq v)$	$p\ (V_r \leq v)$
A vs. B	12	16.5	61.5	0.0922	
C	16	21.0	115.0	0.0130	
D	8	18.0	18.0	1.0000	
B vs. C	16	57.0	79.0	0.5966	
D	13	69.0	22.0		0.1098
C vs. D	16	110.0	26.0		0.0290

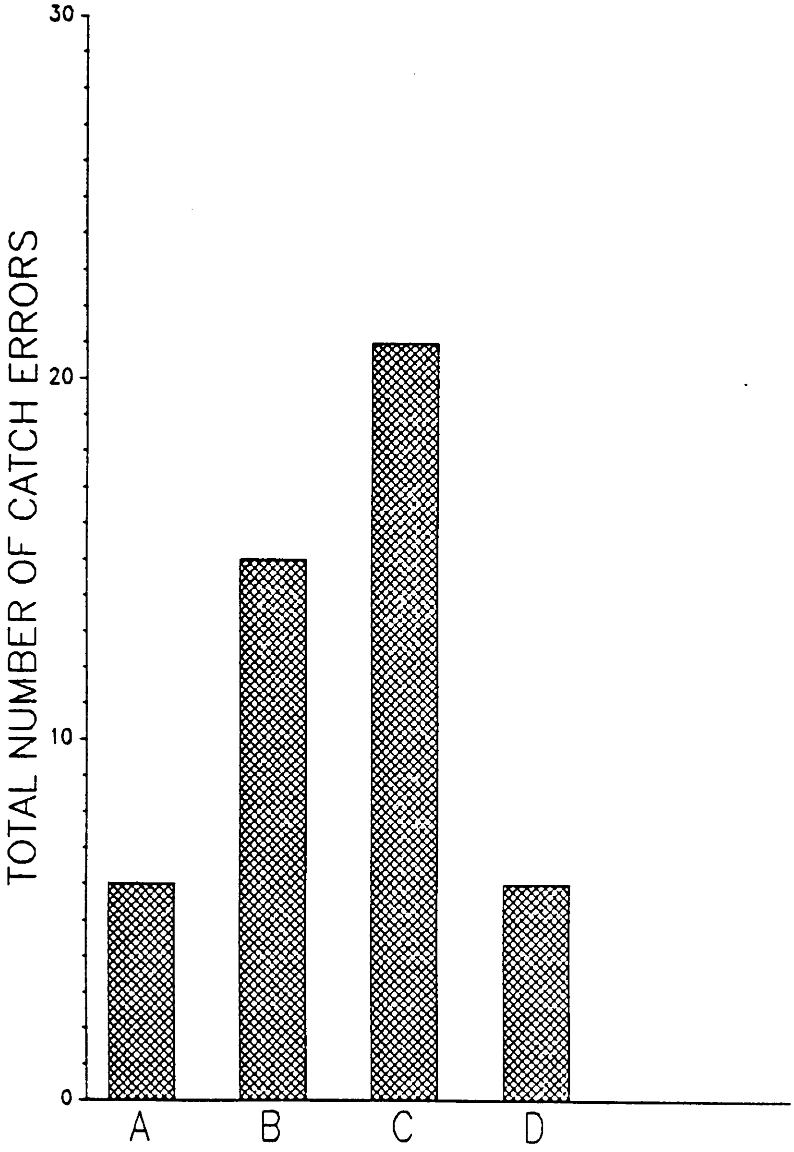

Figure 6: Total number of catch errors occurring below 20 m.p.h. per configuration

error per every 34 foot movements made. In total, 209 such errors were noted throughout the experiment. The frequency with which these errors occurred for each configuration is shown in Figure 7.

An Aligned Ranks Test performed on these data revealed a significant difference among the four configurations, Q (3) = 15.62, $p < 0.0014$, and therefore the Wilcoxon Signed-Ranks Test was again used to determine which configurations differed. A significantly greater number of scuff errors were found for Configuration B than for any of the other configurations. Configuration C also resulted in a significantly higher number of errors than did Configuration D (see Table 10 for the results of all pair-wise comparisons). Symbolically, these results may be expressed as follows:

$$\begin{array}{cccc} D & A & C & B \\ \cline{1-2} \\[-2ex] \cline{2-3} \cline{4-4} \end{array} \qquad \alpha_e = 0.05$$

Also of interest were the pattern of differences at each of the velocity categories. Division of the scuff error data into errors occurring above and below 20 m.p.h. is shown in Figure 8. As with the catch error data, an Aligned Ranks Test was performed on the scuff errors that occurred within each velocity class. This time significant differences were found to exist both for scuff errors occurring above 20 m.p.h., Q (3) = 15.80, $p < 0.0014$, and those occurring at speeds below 20 m.p.h., Q (3) = 17.57, $p < 0.0006$.

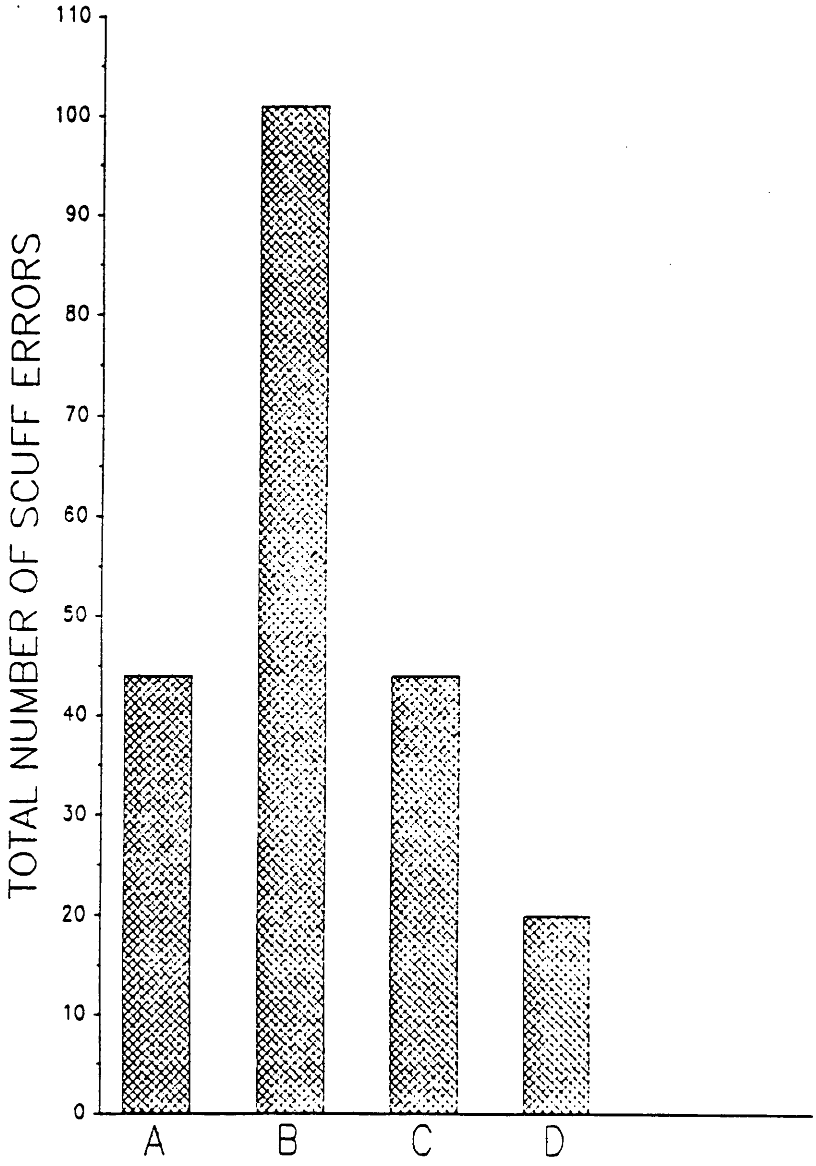

Figure 7: Total number of scuff errors per configuration

TABLE 10

Results of All Possible Pair-Wise Comparisons Using the Wilcoxon Signed-Ranks Test on Total Number of Scuff Errors Per Configuration

Comparison	N	V_s	V_r	p ($V_s \le v$)	p ($V_r \le v$)
A vs. B	19	34.5	155.5	0.014	
C	15	56.0	64.0	0.847	
D	14	81.5	23.5		0.7840
B vs. C	19	156.5	33.5		0.0124
D	23	258.0	18.0		<0.0004
C vs. D	16	120.5	15.5		0.0052

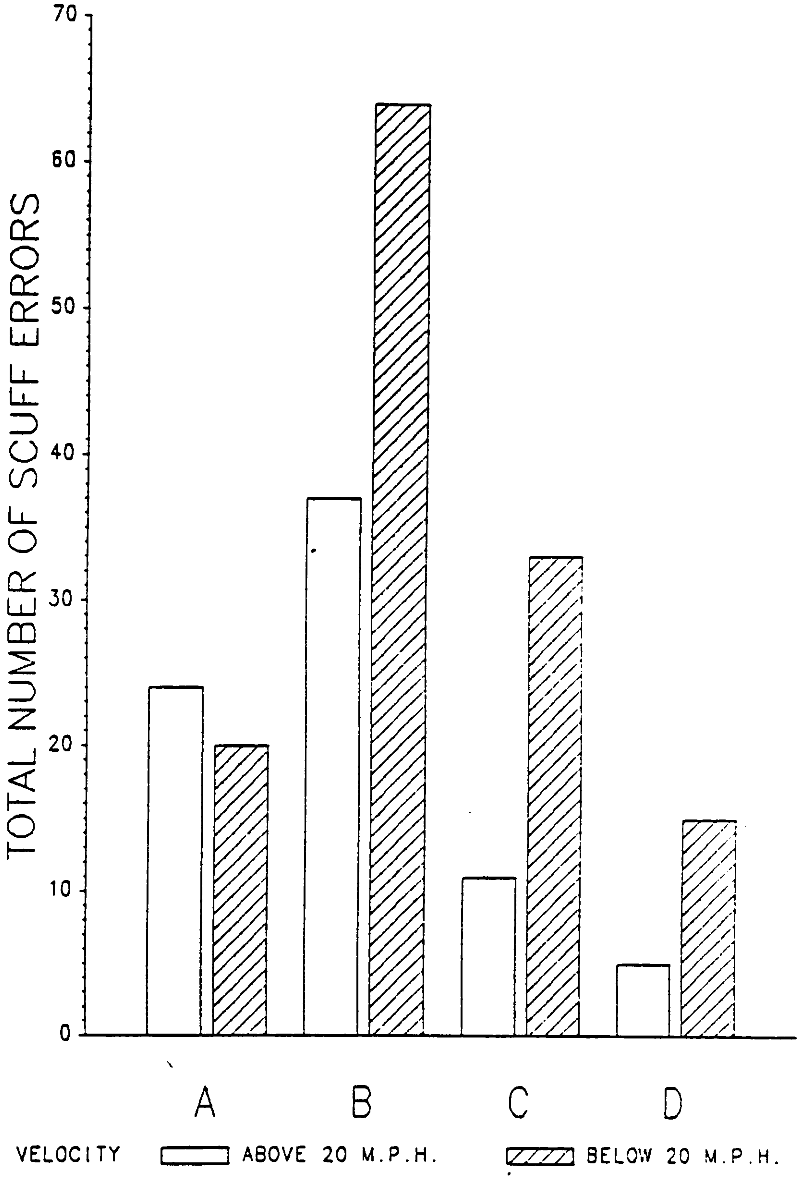

Figure 8: Total number of scuff errors above and below 20 m.p.h. per configuration

The Wilcoxon Signed-Ranks Test was employed to determine which configurations differed within each velocity. For speeds above 20 m.p.h., Configuration B had significantly more errors than did Configurations C or D. Likewise, Configuration A had significantly more scuff errors than did D (see Table 11 for a complete presentation of the pair-wise comparison results). Symbolically, this pattern of results appears as:

$$\begin{array}{cccc} D & C & A & B \\ \cline{1-2} & & & \\[-2ex] \cline{2-3} & & & \\[-2ex] \cline{3-4} \end{array} \qquad \alpha_e=0.05$$

Below 20 m.p.h. the pattern of differences among the four configurations was exactly the same as that noted for total scuffs per configuration. The results of the Wilcoxon Signed-Ranks Tests conducted on this subset of the scuff error data are presented in Table 12, and may be represented as follows:

$$\begin{array}{cccc} D & A & C & B \\ \cline{1-2} & & & \\[-2ex] \cline{2-3} \cline{4-4} \end{array} \qquad \alpha_e=0.05$$

<u>Instructional errors</u>. There were 162 instructional errors in this experiment. They represent an average of almost 7 instructional errors per subject across the entire study. As noted earlier, of particular interest was whether or not differences existed among the four configurations with regard to these errors, since the lack of such differences could be interpreted as representing an unbiased state of affairs (i.e. conditions did not favor one configuration over another). Conducting an Aligned Ranks Test on the instructional error data demonstrated that in

TABLE 11

Results of All Possible Pair-Wise Comparisons Using the Wilcoxon Signed-Ranks Test on Scuff Errors Occurring Above 20 m.p.h.

Comparison	N	V_s	V_r	p ($V_s \leq v$)	p ($V_r \leq v$)
A vs. B	17	48.0	105.0	0.19	
C	11	53.0	13.0		0.083
D	14	90.0	15.0		0.0166
B vs. C	15	110.0	10.0		0.0124
D	16	131.5	4.5		0.0004
C vs. D	10	41.5	13.5		0.1934

TABLE 12

Results of All Possible Pair-Wise Comparisons Using the Wilcoxon Signed-Ranks Test on Scuff Errors Occurring Below 20 m.p.h.

Comparison	N	V_s	V_r	$p\ (V_s \le v)$	$p\ (V_r \le v)$
A vs. B	16	8.0	128.0	0.0008	
C	12	14.5		0.0640	
D	14	65.5	39.5		0.4632
B vs. C	20	158.5	51.5		0.0484
D	21	213.0	18.0		0.0008
C vs. D	15	103.0	17.0		0.0124

fact there were no significant differences among the four configurations with regard to the total number of instructional errors per configuration, $Q\ (3) = 1.33$, $p > 0.05$. Similarly, analyses conducted on each velocity category revealed no configuration differences in instructional error either above 20 m.p.h., $Q\ (3) = 0.98$, $p > 0.05$, or below 20 m.p.h., $Q\ (3) = 1.67$, $p > 0.05$. The total raw number of instructional errors which occurred for each velocity and configuration are presented in Appendix F.

Additional Analyses

In addition to the questions answered by the preceding analyses, specific hypotheses were made earlier which require the analysis of various subsets of the data. In particular the errors of interest include: 1) errors in which both pedals are depressed or touched at the same time, 2) errors where the subject's foot catches on the brake during movement from the accelerator to the brake, and 3) errors in which the subject's foot catches on the brake pedal during movement from the brake to the accelerator.

Following the analyses of these subsets of the data, the effects of three subject variables will be examined, namely the effects of gender, shoe width, and height on the total number of errors per subject. And finally, the movement time results will be presented.

"Both" errors. It was hypothesized that Configuration B would have significantly more errors in which both pedals were depressed than any of the other configurations. Although all the configurations had horizontal separations which were less than the mean shoe width reported by Damon, Stoudt, and McFarland (1966), Configuration B had the smallest horizontal separation and therefore was predicted to have the greatest number of these errors. The number of times in which both pedals were actually depressed was very small (see Appendix E), however, errors in which the foot touched both pedals while actuating either pedal (see the scuff error category in Table 5) was viewed as representing a strong potential for this type of error. These two subsets of the error data were thus combined to determine how the configurations differed with regard to the potential for this class of errors, henceforth referred to as "Both" errors. The distribution of these errors across the four configurations is depicted in Figure 9.

An Aligned Ranks Test was performed on the data with the result that a significant difference among the configurations was found, $Q\ (3) = 20.70$, $p < 0.0002$. Further analyses using the Wilcoxon Signed-Ranks Test revealed that Configuration B did in fact result in a significantly greater number of these errors than did any of the other configurations. Configurations A, C, and D did not differ significantly (see Table 13 for the results of

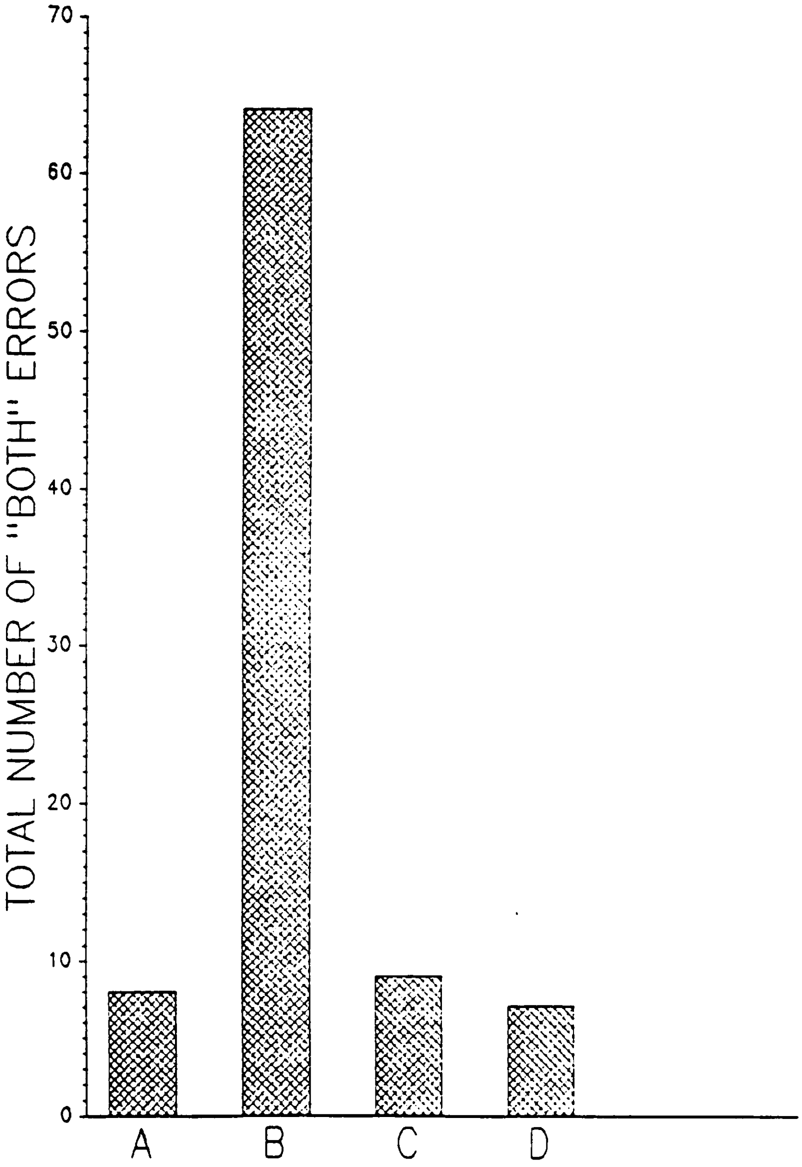

Figure 9: Total number of "Both" Errors per configuration

TABLE 13

Results of All Possible Pair-Wise Comparisons Using the Wilcoxon Signed-Ranks Test on "Both" Error Data

Comparison	N	V_s	V_r	p ($V_s \le v$)	p ($V_r \le v$)
A vs. B	13	0.0	91.0	0.0002	
C	7	14.0	14.0		1.0
D	6	12.0	9.0		0.8438
B vs. C	15	116.5	3.5		0.0004
D	13	91.0	0		0.0002
C vs. D	7	13.0	15.0	0.9376	

all pair-wise comparisons). Symbolically, these results may be represented as:

$$\underline{D\ A\ C}\ \underline{B} \qquad \alpha_e = 0.05$$

"Catch A → B" errors. To test for configuration differences in the number of instances in which the foot caught on the lower right edge of the brake pedal during movement from the accelerator to the brake, two groups of errors were combined. In addition to catches that occurred during accelerator to brake (A → B) movements, instances where the foot "scuffed" the brake during this movement were also included in the analysis (again, as with the "both" error category, scuffing the foot on the brake during A → B movement was viewed as indicating a greater potential for catching the foot on the brake). The distribution of these errors, subsequently referred to as "Catch A → B" errors, across the four configurations is shown in Figure 10.

Performing an Aligned Ranks Test on the data revealed a significant difference among the four configurations, Q (3) = 12.76, $p < 0.006$. Pair-wise comparisons conducted using the Wilcoxon Signed-Ranks Test revealed that Configuration A resulted in a significantly greater number of these errors than did any other configuration. The remaining configurations did not significantly differ with regard to these errors (see Table 14). These results may be symbolically represented by:

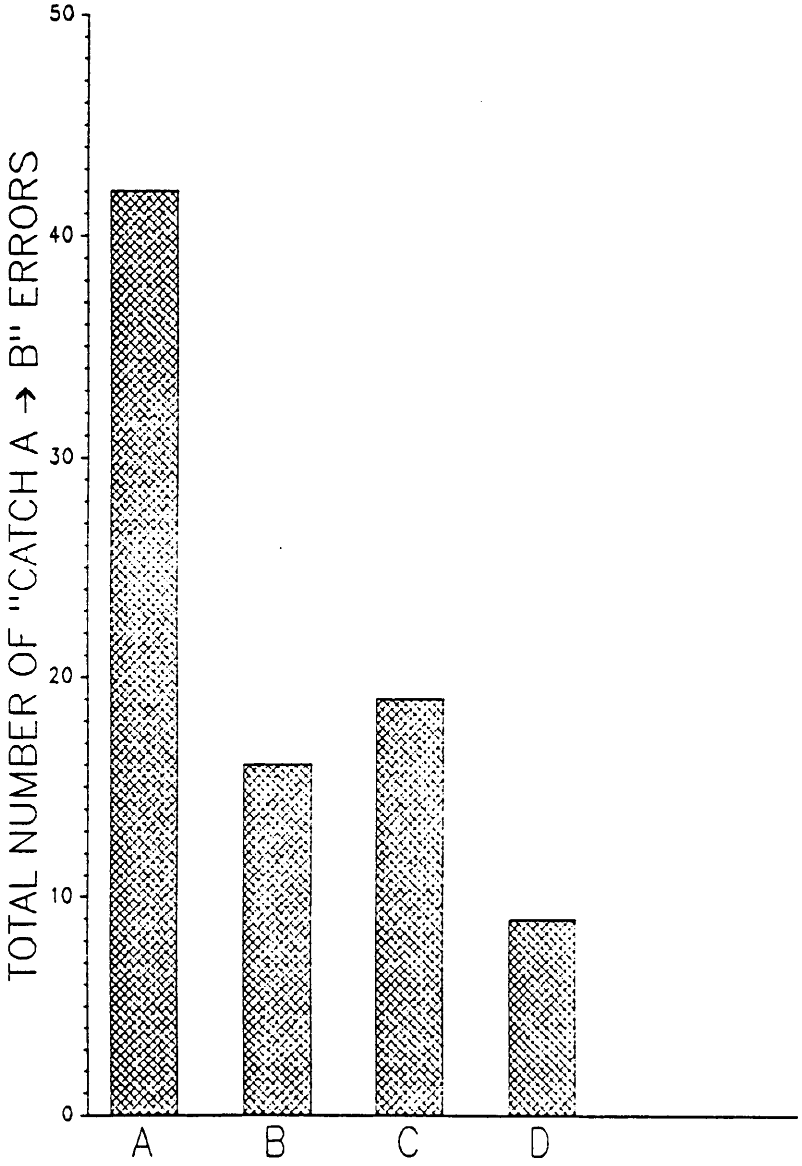

Figure 10: Total number of "Catch A → B" Errors per configuration

TABLE 14

Results of All Possible Pair-Wise Comparisons Using the Wilcoxon Signed-Ranks Test on "Catch A → B" Error Data

Comparison	N	V_s	V_r	p ($V_s \le v$)	p ($V_r \le v$)
A vs. B	12	67.5	10.5		0.0268
C	12	65.0	13.0		0.0424
D	16	121.0	15.0		0.0042
B vs. C	11	32.5	33.5	1.0	
D	15	82.5	37.5		0.2294
C vs. D	13	61.0	30.0		0.3054

D B C A α_e=0.05

Also of interest was whether or not a significant difference could be found between the two velocity categories in terms of these catch errors. Therefore, a Wilcoxon Signed-Ranks Test was conducted on the "Catch A → B" data, comparing the number of these errors occurring at each velocity. The results of this analysis revealed that the two categories did not differ, $\underline{V}_r$ (14) = 28.5, $\underline{p}$ > 0.0676.

Comparing the number of "Catch A → B"errors above and below 20 m.p.h. for *each* configuration, however, revealed that a significant difference between the two categories did exist for Configuration A, but not for the other configurations (see Table 15 for a complete presentation of these results). The direction of this difference was as expected, with a significantly greater number of these errors occurring above 20 m.p.h. than below.

"Catch B → A" errors. An additional subset of data which was of interest in this study combined the brake to accelerator catch and scuff categories from Table 5. Specifically, this included the errors in which the foot caught on the upper right side of the brake during movement from the brake to the accelerator (errors in which the foot caught on the lower left side of the accelerator were not included in this analysis). This set of errors will subsequently be referred to as "Catch B → A" errors. The

TABLE 15

Comparisons of "Catch A → B" Errors Occurring Above and Below 20 m.p.h. for Each Configuration*

Configuration	N	V_s	V_r	$p\ (V_s \leq v)$	$p\ (V_r \leq v)$
A	13	81.5	9.5		0.0052
B	6	6.0	15.0	0.2188	
C	8	14.5	21.5	0.3711	
D	7	17.5	10.5		0.2891

*One-sided tests of significance

total number of these errors observed for each configuration is shown in Figure 11.

Conducting an Aligned Ranks Test on this data revealed the presence of a significant difference among the four configurations, $Q\ (3) = 30.01$, $p < 0.0001$. Application of the Wilcoxon Signed-Ranks Test to the pair-wise comparison of this data for the four configurations uncovered Configuration C as having significantly more catch B → A errors than the other configurations. Configuration A also had significantly more of these errors than did B (see Table 16 for a complete presentation of the pair-wise comparison results). These results may be summarized as follows:

$$\begin{array}{cccc} B & D & A & C \\ \cline{1-2} \cline{4-4} \\[-2.5ex] \cline{2-3} \end{array} \qquad\qquad \alpha_e=0.05$$

Gender. To determine whether there were any differences in the performance of males and females in this study, a two-way analysis (gender x configuration) based on the methods for non-parametric regression specified by Hettmansperger and McKean (1978) was employed. The equivalent F value for a gender main effect was not found to be significant, nor was the F value obtained for a test of a gender by configuration interaction. As would be expected, however, the test for a difference among the four configurations did prove significant, $F\ (3,\ 91) = 4.53$, $p < 0.01$.

Figure 11: Total number of "Catch B → A" Errors per configuration

TABLE 16

Results of All Possible Pair-Wise Comparisons Using the Wilcoxon Signed-Ranks Test on "Catch B → A" Error Data

Comparison	N	V_s	V_r	p ($V_s \le v$)	p ($V_r \le v$)
A vs. B	8	36.0	0		0.0078
C	15	2.5	117.5	0.0004	
D	12	46.5	31.5		0.6220
B vs. C	17	0	153.0	0.0000	
D	6	4.0	17.0	0.2188	
C vs. D	15	120.0	0		0.0000

Shoe width. The mean shoe width of subjects participating in this study was 9.65 cm. To determine whether there was a significant relationship between shoe width and the total number of errors committed by each subject, the Thiel-Sen procedure for performing a non-parametric regression was employed. The significance of the regression may be determined by using the large sample version of the Thiel-Sen statistic (TKS) which is approximately distributed as the unit normal distribution with zero mean and unit variance. The significance of the regression is therefore given by the significance of the corresponding Z-value. The regression line for shoe width vs. total error per subject was found to be significant, TKS = 1.66, p =0.048, and is given by:

$$\# \text{ of errors} = -32.19 + 4.64 \times \text{shoe width}.$$

Analysis of the relationship between shoe width and the total number of errors per subject was then performed separately for each of the configurations. The results of these analyses are presented in Table 17 which shows the Thiel-Sen estimates for the slope and intercept in each case, as well as the corresponding Z-values and their significance. A significant relationship was found for Configuration A, but not for any of the other configurations. The regression line in this instance is given by:

$$\# \text{ of errors} = -9.31 + 1.25 \times \text{shoe width}.$$

TABLE 17

Results of the Theil-Sen Regression of Total Error Per Subject Onto Shoe Width for Each Configuration*

Configuration	Intercept	Estimated Slope	Z	p-value
A	-9.312	1.250	2.22	0.0129
B	-3.338	0.851	1.05	0.1446
C	3.000	0.000	0.076	0.4695
D	1.000	0.000	0.843	0.1993

*one-sided test of significance

Height. The average height of the subjects participating in this study was 174.41 cm. The Thiel-Sen procedure was employed to determine whether a relationship could be found between height and the total number of errors per subject. The resulting regression line was found to be significant, TKS = 2.10, $p = 0.035$, and is given by,

$$\# \text{ of errors: } -102.00 + 0.65617 \times \text{height}$$

where height is measured in centimeters.

As with the shoe width data, regression lines were estimated for each configuration. Of the four regression equations generated, only that obtained for Configuration A was found to be significant (see Table 18). The estimated regression line is given by,

$$\# \text{ of errors} = -26.41 + 0.16584 \times \text{height}$$

where height is again measured in centimeters.

Movement time. The time from release of the accelerator to initial application of the brake could be analyzed using standard parametric methods i.e. using analysis of variance procedures. Analysis of the movement times obtained in this experiment revealed neither a significant effect due to configuration nor a significant configuration by speed interaction. There was, however, a highly significant effect due to vehicle velocity, $F(1,22) = 33.80$, $p = 0.0001$ (See Table 19 for a complete presentation of the analysis of variance results). In this case, subjects' foot movements from the accelerator to the brake

TABLE 18

Results of the Theil-Sen Regression of Total Error Per Subject Onto Height for Each Configuration*

Configuration	Intercept	Estimated Slope	Z	p-value
A	-26.419	0.165	2.13	0.0325
B	-50.237	0.315	1.83	0.0672
C	-10.699	0.078	0.98	0.3240
D	1.000	0.000	1.59	0.1097

*two-sided test of significance

TABLE 19

Analysis of Variance Results for Movement Time Data

Source	df	SS	MS	F	p
Between-Subjects					
Subjects (S)	22*	753993.64	34272.43		
Within-Subjects					
Configuration (C)	3	26105.09	8701.69	2.24	.0918
C x S	66	256388.75	3884.67		
Velocity (V)	1	30129.33	30129.33	33.80	.0001
V x S	22	19612.88	891.49		
C x V	3	3614.30	1204.76	2.53	.0649
C x V x S	66	31466.90	476.77		
Total	183	1121310.93			

*the movement times for one of the 24 subjects were discarded because it was clear the subject was not obeying instructions to brake as quickly as possible.

were significantly faster above 20 m.p.h. than below 20 m.p.h. (276.91 msec vs. 302.56 msec, respectively).

Examination of the significance levels shown in Table 19 reveals that the p-values for the configuration effect and the configuration by speed interaction approach significance at the $\alpha=0.05$ level. Had a larger sample size been used, it is very likely that significance would have been obtained. For this reason, the mean movement times obtained as a function of configuration and velocity are presented in Table 20; however, it must be emphasized that only the main effect due to velocity was significant.

TABLE 20

Mean Movement Time (msec) as a Function of Configuration and Velocity*

	Configuration			
	A	B	C	D
Velocity				
Above 20	280.10	268.76	299.73	259.05
Below 20	308.81	299.51	314.36	297.33

*only the main effect due to velocity was significant

DISCUSSION

Pedal Actuation Errors

The observations of drivers' foot movements made during this study suggest that, for some configurations at least, pedal actuation errors of the sort described in Table 5 may be expected to occur during actual driving. The frequency with which these errors occur varies greatly according to the criticality of the error. Minor errors, such as scuff errors, occur more frequently than catch errors, which in turn occur much more frquently than serious errors. This pattern follows a logical order since it represents increasingly larger deviations in foot movement (one would expect large deviations in foot movement to occur much less frequently than small ones).

The study also suggests that the orientation and arrangement of the pedals will have an effect on the occurrence of some types of error.

Configuration differences in error. As mentioned previously, the fact that a significant difference could not be found among the four configurations with regard to serious errors should be interpreted with caution. Whether this is a result of the extreme sparsity of the data, or is representative of a real non-difference, is not clear. It is evident that much more data would be needed to resolve this issue. Considering that 72 hours of concentrated data were taken in this experiment, it is unlikely, because of the demands placed on system hardware, that the issue can be resolved using simulation laboratory methods. It can be said, however, that serious errors are infrequent.

An important finding with regard to the serious error data is that in the instances in which a subject mistakenly depressed the accelerator instead of the brake, there was <u>no evidence</u> of a <u>sustained</u> effort by the subject to continue depressing the accelerator. Each subject who committed this type of error <u>immediately</u> recognized that a mistake had been made and took action to correct it.

Various other conclusions may be made on the basis of the distribution of the other types of error across the four configurations.

Configuration C demonstrated definite problems with catch and scuff errors. These problems were primarily associated with speeds below 20 m.p.h. This is particularly true of the catch error data for which no differences were noted among the configurations for either the total number of catches or catches above 20 m.p.h., but when catches <u>below</u> 20 m.p.h. were examined, Configuration C emerged as having significantly more errors than either A or D. An examination of the types of catch errors that occurred for C below 20 m.p.h. reveals that over 70% of these were errors in which the subject's foot caught on the upper right edge of the brake during movement from the brake to the accelerator.

In terms of the scuff error data, Configuration C demonstrated a significantly greater number of scuff errors than did Configuration D. Here again, looking at each velocity category separately revealed that Configuration C did not differ significantly from Configuration D above 20 m.p.h., but <u>did</u> prove significantly different from D <u>below</u> 20 m.p.h. At these speeds approximately 54% of the errors observed for C were errors in which the subject's foot scuffed the upper right edge of the brake during B → A movement.

The analysis conducted on the "Catch B → A" data for the four configurations (see Results section) indicated that a significantly greater number of these errors occurred for Configuration C than for any of the other configurations, which did not significantly differ. This would lead one to speculate that much of the catch and scuff error problems found for C may in fact be due to this type of error. This would explain the fact that the scuff and catch error differences noted above disappeared when speeds above 20 m.p.h. were examined, since there were seven times as many B → A movements below 20 m.p.h. as above for each configuration (see Table 4). Perhaps sufficient opportunity was provided below 20 m.p.h. for this type of effect to be detected, while the effect was not strong enough to be noticed with the smaller number of B → A movements that occurred above 20 m.p.h.

Configuration B demonstrated particular problems with scuff errors. A significantly greater number of scuff errors was observed for Configuration B than for any other configuration. The greatest percentage of these errors (approximately 60%) were errors in which the foot nudged the side of the other pedal while depressing either the accelerator or the brake. Configuration B demonstrated the same propensity toward scuff errors within each of the velocity categories, resulting in a significantly greater number of scuff errors than any of the other configurations below 20 m.p.h., and significantly more scuffs than either C or D above 20 m.p.h. In either case, nudging the other pedal while actuating either the brake or accelerator represented the greatest percentage of the errors observed for Configuration B (67% and 53% of the errors occurring at speeds above and below 20 m.p.h., respectively).

Analysis of the "Both" error data (the reader will remember that this category contained not only errors in which the other, non-actuated pedal was nudged aside but also included instances in which both pedals were actually depressed) revealed that Configuration B resulted in a significantly greater number of these errors than did any of the other configurations which did not significantly differ. Thus, it appears that the problems associated with B were primarily ones in which there was insufficient space available to actuate one of the pedals without touching or depressing the other.

The problems associated with Configuration A are not apparent at speeds below 20 m.p.h. At these velocities Configuration A did not significantly differ from Configuration D which demonstrated the lowest incidence of error in each of the major error categories. In terms of the <u>total</u> number of errors, however, Configuration A did result in a significantly greater number of errors than did D. When the total error for each velocity category is examined separately, it is discovered that the two configurations did not differ below 20 m.p.h., but did differ at speeds above 20 m.p.h., with Configuration A resulting in a greater number of errors than either C or D.

This same pattern is noted for the scuff error data. Configurations A and D did not significantly differ with regard to the total number of scuffs per configuration. Neither did they differ at speeds below 20 m.p.h. At higher velocities, however, Configuration A was found to result in a significantly greater number of scuff errors than Configuration D. Examination of the types of scuff errors that occurred for A at these speeds reveals that the largest percentage of the errors observed (approximately 83%) were errors in which the subject's foot scuffed the lower right edge of the brake during movement from the accelerator to the brake. Combining the scuff errors with the corresponding error category from the catch error data (i.e.

instances in which the subject's foot actually caught on the brake pedal during A → B movement) and analyzing the resulting data for the four configurations, revealed that Configuration A resulted in a significantly greater number of these errors than did any of the other configurations which did not significantly differ. This result is somewhat surprising. It was hypothesized that Configuration C which had the largest vertical separation of all the configurations would also result in a significantly greater number of these errors than either B or D. The present results indicate that this was clearly not the case, subjects did not perform significantly worse with C than they did with B or D. This suggests a possible interaction between the vertical and horizontal pedal separations. It may be that the angle of approach of the foot to the brake, as determined by these parameters, is an important factor to be considered. This angle is very similar for Configurations B, C, and D (32.87°, 30.38°, and 30.21°, respectively), while for Configuration A it is much larger (41.61°). It is not known at present whether this is in fact the reason for the results observed here, however, it does provide an interesting question to be answered by future research.

The appearance of a significant difference between A and D at speeds greater than 20 m.p.h. when no such difference was found to exist below 20 m.p.h. brings into question whether differences may exist between the two velocity categories with regard to the number of A → B catches occurring at each speed. A comparison of the two speed categories, collapsing across configurations, demonstrated that overall, at least, this did not occur. <u>However</u>, comparisons of the "above" and "below" Catch A → B data for <u>each</u> configuration revealed that while the same was true for Configurations B, C and D, a difference was found for Configuration A. The direction of this difference was as expected, with a greater number of A → B catches occurring above 20 m.p.h. than below.

It is suspected that the failure to detect a velocity effect for Configurations B, C or D is a consequence of the small number of A → B errors that occurred for these configurations. Theoretically, there is no reason to suppose that the effect observed for A should not also be observed for the other configurations, if more data had been collected.

Originally, it was thought that the presence of a significantly larger number of A → B catches above 20 m.p.h. than below, would serve as evidence that distance cues were being used instead of location cues in the programmed movements from the accelerator to the brake (see Literature Review). While this would serve to explain the velocity differences noted, another explanation is possible. In the event that the average velocity of A → B movements above 20 m.p.h. is greater than the average velocity below 20 m.p.h., an increase in the variable error of the movement would be expected. The end result would be the A → B error difference noted above. Although it is not known whether A → B movements above 20 m.p.h. were on the average actually faster than A → B movements below 20 m.p.h., the fact that this was true for the emergency A → B movements makes this a viable possibility. Regardless of the explanation, however, the fact remains that a difference in A → B error was found between the two velocity categories for one of the configurations.

Of the four configurations included in this study, Configuration D proved to be superior in terms of minimizing the number of pedal actuation errors. Each of the other three configurations demonstrated a susceptability to some subset of the errors observed. Configuration C proved to be vulnerable to errors in which the subject's foot scuffed or caught on the brake during movement from the brake to the accelerator. For Configuration B, it was problems with touching or depressing both pedals. Configuration A demonstrated problems with the subject's foot scuffing or catching on the right edge of the brake during movement from the accelerator to the brake. Configuration D, however, with the exception of the Catch B → A data, was associated with the minimum number of errors regardless of the type of error or velocity considered. And even in the case of the

Catch B → A data, Configuration D was not significantly different from Configuration B which had the smallest number of these errors. It can be concluded, therefore, that in terms of minimizing the number of pedal actuation errors, Configuration D would be the preferred configuration.

Unfortunately, an insufficient amount of data was available to test the hypothesis that Configurations A and D would result in a greater number of instances in which the foot caught on either pedal during movement from the floor. This type of error occurred only six times throughout the entire experiment. It is evident that more data would be needed to resolve this issue.

Effects of shoe width and height. From the data gathered here, it appears that drivers with larger shoe widths will experience a greater number of errors with Configuration A than drivers with smaller feet. As mentioned previously, the greatest percentage of the errors associated with Configuration A were errors which the subject's foot scuffed or caught on the brake during movement from the accelerator to the brake. It could be hypothesized that the larger shoe widths did not allow for as much lateral variability in the movement as did the smaller shoe widths (in other words, there was less clearance between the pedal and the larger shoe widths), thus resulting in a greater number of errors during the upward movement to the brake. Although Configuration C also had a vertical separation similar to that of A, it is possible that the larger horizontal separation allowed for more variability in the horizontal component of the movement without the foot catching on the brake so that no relationship between error and shoe width was found for this configuration.

The significant relationship between height and total error per subject found for Configuration A is somewhat more puzzling. It seems plausible that the taller subjects may have encountered some interference with the simulator's steering apparatus during movement to the higher brake, however, all of the subjects, when first observed sitting in the simulator at the beginning of each session, appeared to have more than ample room to operate the pedals without this type of interference occurring. It is doubtful, therefore, that this is a satisfactory explanation for the observed relationship.

Movement Time

The failure to find a significant difference in movement time among the four configurations of the present study should not be interpreted as being a contradiction of the results of previous research which has shown that increasing the level of the brake pedal above the accelerator results in an increase in movement time. Most of these studies have typically included configurations for which the difference in vertical separation was at least 5.08 cm. Thus, it is quite likely that the differences in vertical separation included among the configurations of the present study were not large enough to enable the effect to be detected with the sample size used (the largest difference in vertical separation occurred between Configurations C and D, and was only 2.07 cm).

It is interesting that a significantly smaller mean movement time was found above 20 m.p.h. than at slower speeds. Perhaps at these faster speeds subjects felt that, as in the real world, there was less time available in which to stop the car, and so the situation became much more "urgent" at high velocities than at slower speeds.

Conclusions

Many investigators have expressed concern over various pedal design recommendations and practices because of the possibility of pedal actuation errors (e.g. Glass and Suggs, 1977; Snyder, 1976). The present experiment provides empirical evidence that pedal actuation errors do occur, and with the exception of serious errors and some categories of catch errors are configuration-dependent. Several other conclusions may be made based on the data from this study.

Based on the results obtained for Configurations A and D it may be concluded that increasing the vertical separation between the accelerator and a "higher" brake pedal (without a corresponding increase in horizontal separation) will have a detrimental effect on performance. Comparisons between these two configurations indicate that there will not only be an increase in the total number of errors with the higher brake pedal, but also an increase in the number of times in which the driver's foot catches or scuffs the brake during accelerator to brake movement. This latter type of error could potentially result in a delay in braking and, therefore, an increase in stopping distance. Thus, from the standpoint of both movement time and pedal actuation errors, increasing the vertical separation of a higher brake configuration is an unacceptable design decision.

Most of the concern over pedal actuation errors has focused on the possibility of the driver concurrently depressing both pedals. Although this concern has previously been based on speculation that these errors could occur during driving, the present research provides evidence that these errors do in fact occur for some configurations currently in use. Differences exist among these configurations with regard to the potential for this type of error. Configuration B, for example, with its 5.40 cm horizontal separation resulted in a significantly greater number of instances in which the foot concurrently touched or depressed both pedals than did any of the other configurations. It should be noted, however, that all of the configurations had horizontal separations which were less than the mean shoe width of the subjects. As a result, this type of error was observed for each of the configurations used in the study. It is apparent that the horizontal separation between the pedals must be increased if the possibility for this type of error is to be eliminated.

It is obvious that the majority of the errors documented in this thesis (with the exception of the serious error category) are not likely to be of life-threatening consequence to the driver. <u>However</u>, if the goal of human factors is truly optimization of the human/machine interface, it is apparent from this research that pedal design practices currently in use are somewhat less than "optimal". Changes need to be made in the design and placement of the automobile's accelerator and brake to ensure a more compatible fit between driver and automobile.

REFERENCES

Beggs, W.D.A., and Howarth, C.I. (1970). Movement control in a repetitive motor task. Nature, 225, 752-753.

Beggs, W.D.A., Andrew, J.A., Baker, M.L., Dove, S.R., Fairclough, I., and Howarth, C.I. (1972). The accuracy of non-visual aiming. Quarterly Journal of Experimental Psychology, 24, 515-523.

Chapanis, A. and Kinkade, R.G. (1972). Design of Controls. In H.P. VanCott and R.G. Kinkade (Eds.), Human engineering guide to equipment design (rev. ed.) (pp. 345-349). Washington D.C.: American Institutes for Research.

Crossman, E.R.F.W. and Goodeve, P.J. (1963). Feedback control of hand movements and Fitts' Law. Paper presented at the Experimental Psychology Meeting. Oxford, England, 1963. Published in Quarterly Journal of Experimental Psychology, 35A, 251-278.

Damon, A., Stoudt, H.W., and McFarland, R.A. (1966). The human body in equipment design. Cambridge, Massachusetts: Harvard University Press.

Davies, B.T. and Watts, J.M., Jr. (1969). Preliminary investigation of movement time between brake and accelerator pedals in automobiles. Human Factors, 11, 407-410.

Davies, B.T. and Watts, J.M., Jr. (1970). Further investigations of movement time between brake and accelerator pedal in automobiles. Human Factors, 12, 559-561.

Drury, C.G. (1975). Application of Fitt's Law to foot-pedal design. Human Factors, 17 (4), 368-373.

Fitts, P.M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology, 47, 381-391.

Fitts, P.M., and Peterson, J.R (1964). Information capacity of discrete motor responses. Journal of Experimental Psychology, 67, 103-112.

Fullerton, G.S., and Cattell, J. McK. (1892). On the perception of small differences. University of Pennsylvania Philosophical Series, No. 2

Glass, S.W. and Suggs, C.W. (1977). Optimization of vehicle accelerator-brake pedal foot travel time. Applied Ergonomics, 8 (4), 215-218.

Glencross, D.J. and Anderson, G.A. (1976). Operator response factors in the location and control of foot pedals. Ergonomics, 19 (4), 399-408.

Gundry, J. (1975). The use of location and distance in reproducing different amplitudes of movement. Journal of Motor Behavior, 7 (2), 91-100.

Hertzberg, H.T.E. and Burke, F.E. (1971). Foot forces exerted at various aircraft brake-pedal angles. Human Factors, 13 (5), 445-456.

Hettmansperger, T.P. and McKean, J.W. (1978). Statistical inference based on ranks. Psychometrika, 43(1), 69-79.

Howarth, C.I. and Beggs, D.A. (1985). The control of simple movements by multisensory information. In: H. Heuer, U. Kleinbeck, and K.H. Schmidt (Eds.), Motor behavior: Programming, control, and acquisition. Berlin: Springer.

Howarth, C.I., Beggs, W.D.A., and Bowden, J.M. (1971). The relationship between the speed and accuracy of movement aimed at a target. Acta Psychologica, 35, 207-218.

Keele, S.W. (1968). Movement control in skilled motor performance. Psychological Bulletin, 70, 387-403.

Keele, S.W. (1981). Behavioral analysis of movement. In Brooks V. (Ed.) Handbook of physiology: The nervous system. Vol. 2. Motor control. Baltimore: American Physiological Society.

Lehmann, E.L. (1975). Nonparametrics: statistical methods based on ranks. San Francisco: Holden-Day.

Meyer, D.E., Smith, J.E.K., and Wright, C.E. (1982). Models for the speed accuracy of aimed limb movements. Psychological Review, 89, 449-482.

Morrison, R. W., Swope, J. G., and Halcomb, C. G. (1986). Movement time and brake pedal placement. Human Factors, 28 (2), 241-246.

Newell, K.M. and Carlton, L.G. (1985). On the relationship between peak force and peak force variability in isometric tasks. Journal of Motor Behavior, 17, 230-241.

Newell, K.M., Carlton, L.G., and Carlton, M.J. (1982). The relationship of impulse to timing error. Journal of Motor Behavior, 14, 24-45.

Newell, K.M., Carlton, L.G., and Hancock, P.A. (1984). A kinetic analysis of response variability. Psychological Bulletin, 96, 133-151.

Schmidt, R.A., Zelaznik, H.N., and Frank, J.S. (1978). Sources of inaccuracy in rapid movement. In G.E. Stelmach (Ed.), Information processing in motor control and learning. New York: Academic.

Schmidt, R.A., Zelaznik, H.N., Hawkins, B., Frank, J.S., and Quinn, J.T. Jr. (1979). Motor output variability: A theory for the accuracy of rapid motor acts. Psychological Review, 86, 415-451.

Sexton, D.J. and Koppa, R.J. (1980). Optimization of foot pedal placement in commercial school buses. In Proceedings of the 24th Annual Meeting of the Human Factors Society (pp. 634-637). Los Angeles, CA: Human Factors Society.

Snyder, H.L. (1976). Braking movement time and accelerator-brake separation. Human Factors, 18, 201-204.

Southall, D. (1985). The discrimination of clutch-pedal resistances. Ergonomics, 28(9), 1311-1317.

Stephens, M.A. (1974). EDF statistics for goodness of fit and some comparisons. Journal of American Statistical Association, 69, 730-737.

U.S. Department of Defense. MIL-STD-1472C. Military standard: Human engineering design criteria for military systems, equipment and facilites. Washington, D.C., May 2, 1981.

Welford, A.T. (1968). Fundamentals of skill. London: Methuen.

Wierwille, W.W. (1975). Driving simulator design for realistic handling. In Sachs, H.k. (Ed.) Proceedings, Third International Conference on Vehicle System Dynamics (pp. 446-456). Amsterdam, Netherlands: Swets and Zeitlinger.

Winer, B.J. (1971). Statistical Principles in Experimental Design (2nd ed.). New York: McGraw-Hill, Inc.

Woodson, W.E. (1981). Human Factors Design Handbook. New York: McGraw-Hill, Inc.

Woodworth, R.S. (1899). The accuracy of voluntary movements. Psychological Review. Monograph Supplement 3, Whole No. 13, No. 3.

Zelaznik, H.N., McColsky, D., and Shapiro, D.C. (1981). Effects of a secondary task on the accuracy of single aiming movements. *Journal of Experimental Psychology: Human Perception and Performance*, *7* (5), 1007-1018.

APPENDICES

APPENDIX A

Sample Scenario

Foot Movement	Task
	Initial Condition: the car is in park and in the middle of the right lane; both of the subject's feet are on the floor of the automobile.
F → B	Place the car in reverse.
B → A	Back up approximately 100 ft.,
A → B	and apply your brakes to stop the car.
	Place the car in drive.
B → A	Accelerate to 20 m.p.h.
A → B	Pull to the right side of the road and stop.
	Place the car in reverse.
B → A	Back up approximately 50 ft.
A → B	and apply your brakes to stop the car.
B → F	Place the car in park and put both feet on on the floor.
F → B	Place the car in drive.
B → A	Pull onto the road and accelerate to 55 m.p.h.
A → B	Emergency stop, dash light comes on.
B → A	Accelerate to 20 m.p.h.
A → B	Emergency stop, dash light comes on.
B → A	Accelerate to 40 m.p.h.
A → F	Place both feet on the floor, allow the car to coast to 30 m.p.h.

F → A	and maintain that speed.
	Let up off the accelerator, let the car coast to 20 m.p.h. and then maintain that speed.
A → B	Apply your brakes to stop the car.
B → A	Accelerate to 20 m.p.h.
	Change to the left lane.
A → F	Place both feet on the floor, allow the car to coast to 10 m.p.h. and maintain that speed.
F → B	Emergency stop, dash light must come on before subject moves foot from floor to accelerator.
B → F	Place the car in park and put both feet on the floor.
F → B	Place the car in drive.
B → A	Accelerate to 20 m.p.h.
A → B	Apply your brakes and slow to 10 m.p.h.
B → A	and maintain that speed.
	Accelerate to 30 m.p.h.
A → B	Apply your brakes to stop the car.
B → A	Accelerate to 55 m.p.h.
A → B	Emergency stop, dash light comes on.
B → A	Accelerate to 40 m.p.h.
A → F	Place both feet on the floor, allow the car to coast to 30 m.p.h. and maintain that speed.
F → B	Emergency stop, dash light must come on before

subject moves foot from floor to accelerator.

B → A Accelerate to 20 m.p.h.

Move the car back into the right lane.

A → B Apply your brakes and slow the car to 10 m.p.h.

B → A and maintain that speed.

Accelerate to 20 m.p.h.

A → F Place both feet on the floor,

allow the car to coast to 10 m.p.h.

F → A and maintain that speed.

Accelerate to 55 m.p.h.

A → B Apply your brakes to stop the car.

B → A Accelerate to 40 m.p.h.

A → B Apply your brakes, slow to 30 m.p.h.

B → A and maintain that speed.

Accelerate to 55 m.p.h.

A → B Apply your brakes, slow to 30 m.p.h.

B → A and maintain that speed.

Let off the accelerator, allow the car to coast to 20 m.p.h. and maintain that speed.

A → B Emergency stop, dash light comes on.

APPENDIX B

Instructions and Informed Consent

The purpose of this experiment is to evaluate four different automobile designs on the basis of driver performance. The study is being conducted at the Vehicle Simulation Laboratory, Department of Industrial Engineering and Operations Research, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061, telephone number 961-7962. The research team consists of four graduate students in Industrial Engineering and Operations Research: Jonathan Antin, Tom Dingus, Melissa Hulse and Steve Rogers, under the supervision of Dr. Walter W. Wierwille, Professor of Industrial Engineering and Operations Research and principal investigator in the study.

During the experiment you will be asked to drive an automobile simulator in a simulated driving scenario. You will be asked to perform a series of normal driving tasks that you would possibly encounter in your everyday driving. Instructions to perform each of these tasks will be presented to you by a tape recorded message. Please listen to the entire command for each task before you begin to perform that task. Each scenario will begin with the car in park and in the middle of the right lane. Please try not to change lanes unless you are told to do so. Occasionally you will be required to make a simulated emergency stop. Whenever you see the red light on the dash illuminated, apply your brakes as quickly as you can to bring the vehicle to a stop. To acquaint you with the simulator and the experimental procedure to be used, you will be given a short practice period to drive the simulator before testing begins. Please drive the simulator as you would drive a normal automobile in a safe manner. You will be required to wear a lap seat belt at all times during simulator operation.

If at any time during the experiment you wish to discontinue your participation, you may do so. For your own safety, however, it is important that you remain seated and keep your lap belt fastened until the motion platform has come to a full and complete stop. If at any time you do decide to exit the simulator, you may use either of the two procedures listed below:

1. a) Inform the experimenter of your decision to stop.
   b) Remain seated until the similator has come to a complete and full stop.
   c) Upon instructions from the experimenter, disconnect the lap belt and exit the simulator allowing the experimenter to assist you in doing so.
2. a) Inform the experimenter of your decision to stop.
   b) Press the emergency button on the dash.

c) Remain seated with the lap belt in place _until the experimenter can assist you in exiting_.

Although you should feel free to stop at any time, please complete the driving scenario if you possibly can. If you stop prior to completion of the data runs, we will be unable to use _any_ of your data.

All the data collected during the experiment will be handled anonymously. Keep in mind that this study is not designed to test your driving skill, but only to evaluate certain automobile designs on the basis of driving performance. Therefore, please try to drive as you normally would.

You will be required to return to the laboratory for three other sessions similar to the one conducted today. At the completion of your participation in the study, you will be paid at the rate of $5 per session. If you complete all four sessions, you will receive a $5 bonus. We will be glad to answer any questions you may have concerning the experiment or your rights as a participant, although some questions may have to wait until the completion of your participation in order to avoid influencing the outcome of the study. Please do not discuss the experiment with anyone until the data collection for all participants has ended. Data collection is expected to be completed by March 1, 1986.

PARTICIPANT'S INFORMED CONSENT

The purpose of this document is to obtain your consent to participate in this experiment and to inform you of your rights as a participant.

(1) You have the right to stop participating in the experiment at any time. If you choose to terminate the experiment, you will receive pay only for the time you participated in the experiment.

(2) You have the right to be informed of the overall results of the experiment. If, after participation, you wish to receive summary information about this study, please include your address (4 months hence) with your signature below. If more detailed information is desired after receiving the results summary, please contact the Vehicle Simulation Laboratory, and a full report will be made available to you as soon as possible.

The only known risk associated with this experiment is a risk of injury if you attempt to exit the simulator prior to simulator motion being stopped or without the help of one of the investigators.

The faculty and graduate students involved in this study greatly appreciate your help as a participant. If you have any questions about your rights as a participant, you may contact Mr. Charles D. Waring, Chairman of the University committee on human subjects, at 961-5284.

Your signature below indicates that you have read and understood the above stated rights and risks and that you consent to participate in the study as described. If you include your printed name and address below, a summary of the experimental results will be sent to you.

____
Signature

____
Date

____
Witness Date

____
____
____
Printed Name and Address

Vehicle Simulation Lab
IEOR Department
Virginia Tech
Blacksburg, VA 24061
961-7962

APPENDIX C

Kolmogorov-Smirnov Test Results for Normal Distribution

ERROR CATEGORY	CONFIGURATION A	B	C	D
TOTAL ERROR	1.140*	.742	.671	1.426*
CATCH ERRORS	1.687*	1.566*	1.271*	2.054*
SCUFF ERRORS	1.450*	1.134*	1.205*	1.647*

*significant at $p < 0.01$

Kuiper Test Results for Normal Distribution

ERROR CATEGORY	CONFIGURATION A	B	C	D
TOTAL ERROR	2.050*	1.403	1.279	2.495*
CATCH ERRORS	3.039*	2.558*	2.131*	3.410*
SCUFF ERRORS	2.295*	2.071*	2.139*	3.320*

*significant at $p < 0.01$

APPENDIX D

Obstacles to using a multiple regression approach to analyze the data of the present experiment occur for the following reasons: 1) a multiple regression approach assumes a continuous distribution of the data (the error data gathered for this experiment were count or frequency data), 2) a multiple regression approach assumes that the data for each configuration will be normally distributed (this is clearly not the case for two of the four configurations used here), 3) there are only four distinct "X" points in the data space, which means that only three parameters other than the intercept can be estimated in the model, and finally, and perhaps most importantly, 4) there is a great deal of collinearity among the four configurations with regard to the parameters of interest (this is particularly true regarding the horizontal pedal separations and the brake pedal widths of the configurations). In lieu of these problems, the following results should be interpreted with extreme caution.

To determine the pedal parameters (or combinations of parameters) which accounted for the greatest amount of the variability in the data, the R^2 values for alternative models were calculated and then compared.

The one variable model accounting for the greatest variability in the data is represented by the following equation:

$$\# \text{ of errors} = 1.97 + 0.098 \times \text{brake width} \qquad \text{(A1)}$$

where brake pedal width is measured in centimeters. This model, however, accounted for only 0.3 % of the variation in the data and was not found to be significant ($p > 0.05$).

The best two variable model that could be found accounted for approximately 16 % of the variability in the data and was highly significant, $\underline{F}$ (2, 93) = 8.62, $\underline{p} < 0.0004$. This model is given by the following equation:

$$\begin{aligned}\# \text{ of errors} = {} & -25.84 + 3.55 \times (\text{brake width}) \\ & - 0.01 \times (\text{horizontal sep.})^2 \qquad \text{(A2)}\end{aligned}$$

where brake pedal width and horizontal separation are measured in centimeters.

The addition of the third variable to the model which resulted in the greatest increase in R^2, produced a three variable model which explained approximately 18 % of the variability in the data, however, the estimated regression coefficient for this parameter was not found to be significant ($p > 0.05$). Therefore, the above two-variable model was chosen as the model which best explained the variability in the data.

The model given by Equation A2 reveals that 15 % of the variability in the error data may be accounted for by the width of the brake pedal and the horizontal separation between the pedals. The coefficients of the variables in the model suggest that the number of errors may be decreased by reducing brake pedal width and/or increasing lateral separation. It is likely that the latter would result in fewer instances in which the subject's foot simultaneously touched both pedals, and that the former would reduce the number of instances in which the driver's foot caught on the upper edge of the brake pedal during movement from the brake to the accelerator (both of these errors were relatively frequent in the present experiment); however, generalization of these "recomendations" beyond the scope of the present experiment should be done with extreme caution. While it may be true that these modifications would result in a decrease in the number of types of errors observed here, it is also possible that these changes could result in other errors not noted in the present experiment. For example, decreasing the width of the brake pedal and moving it further away from the accelerator could result in errors in which the driver misses the brake entirely. It must be remembered that the validity of Equation A2 is based solely on the data of the present experiment, and as such, may have application only for the types of errors observed in this study.

APPENDIX E

Number and Types of Serious Errors Occurring for Each Configuration (Raw errors are shown; differences are not significant.)

Error	Configuration			
	A	B	C	D
The subject:				
a) depresses the accelerator instead of the brake	1	0	1	0
b) depresses the brake instead of the accelerator	1	0	1	0
c) depresses both pedals while depressing the accelerator	4	4	1	1
d) depresses both pedals while depressing the brake	0	0	1	0

APPENDIX F

Total Number of Errors Occurring Above and Below 20 m.p.h. Per Configuration (Raw errors are shown.)

SERIOUS ERRORS

CONFIGURATION

		A	B	C	D
VELOCITY	> 20 m.p.h.	2	3	1	0
	< 20 m.p.h.	4	1	3	1

CATCH ERRORS

CONFIGURATION

		A	B	C	D
VELOCITY	> 20 m.p.h.	11	6	4	4
	< 20 m.p.h.	6	15	21	6

SCUFF ERRORS

CONFIGURATION

VELOCITY		A	B	C	D
	> 20 m.p.h.	24	37	11	6
	< 20 m.p.h.	20	64	33	15

INSTRUCTONAL ERRORS

CONFIGURATION

VELOCITY		A	B	C	D
	> 20 m.p.h.	31	38	32	30
	< 20 m.p.h.	8	7	10	4