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Driver Brake and Accelerator Controls and Pedal Misapplication Rates in North Carolina

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16. Abstract
After a 2010 study of the phenomenon of unintended acceleration (UA), the National Highway Traffic Safety Administration (NHTSA) found that pedal misapplication could be a cause of many UA claims, specifically when drivers intend to apply the brake but instead apply the accelerator. Consequently, NHTSA determined that it would be worthwhile to study elements of vehicle pedal design and location to see if they might contribute to the propensity for pedal misapplication. Previous research efforts into UA hypothesized that certain design criteria such as lateral separation, the horizontal gap between the brake and accelerator pedal, and the distance between the surface planes of the brake and accelerator may contribute to driver error.

As an exploratory effort, NHTSA conducted a quantifiable study of the relative locations of pedals in a limited set of passenger cars at its Vehicle Research and Test Center (VRTC) to determine whether elements of vehicle pedal design and location contribute to the propensity for pedal misapplication. Vehicles from populations of low and high rates of pedal misapplication were selected and dimensional variables as defined by an industry standard were measured. Since it was the only source of such comprehensive information, make and model information for pedal misapplication events were taken from the North Carolina State Crash Database. A NHTSA software program was used to define vehicle groups that were substantially similar based on factors such as brand, model, and vehicle wheelbase. North Carolina vehicle registration records were used to limit the vehicles studied to passenger vehicle groups with over 100,000 model-years of exposure in the State with high misapplication rate (HMR) and low misapplication rate (LMR). Ten HMR models and 10 LMR models were selected for study. In addition, 12 models were selected for special interest, including vehicles with the highest exposure that did not fall in either of the previous groups, vehicles similar to HMR or LMR models with significantly different rates, and a vehicle that was the subject of a previous investigation into pedal misapplication.

Three vehicles of each model were located and measured. A statistical correlation of the measurements was conducted and for the first stage of the study, only vehicle dimensions were considered. No single variable had a high correlation to the misapplication rate, though stepover and accelerator position were the most correlated. Standard stepwise regression procedures produced an R^2 value of 0.476, indicating a general relationship. After exhausting pedal variable data, a second analysis was performed that added variables regarding driver characteristics including age, height, and gender. This improved the model significantly and produced an overall R^2 of 0.94. The addition of this data also inverted the correlation with stepover by indicating that higher stepover may specifically be related to higher pedal misapplication rates for older drivers, though this does not suggest that low stepover is not an issue for drivers in general. The results of the study indicate that adding driver characteristics with pedal dimensions affects the predicted rate and that optimal pedal dimensions for one demographic may not be optimal for another.

17. Key Words
Pedal misapplication, unintended acceleration, stepover

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EXECUTIVE SUMMARY

After a 2010 study of the phenomenon of unintended acceleration (UA), the National Highway Traffic Safety Administration found that pedal misapplication could be a cause of many UA claims, specifically when drivers intend to apply the brake but instead apply the accelerator. Consequently, NHTSA determined that it would be worthwhile to study elements of vehicle pedal design and location to see if they might contribute to the propensity for pedal misapplication. Previous research efforts into UA hypothesized that certain design criteria such as lateral separation, the horizontal gap between the brake and accelerator pedal and the distance between the surface planes of the brake and accelerator may contribute to driver error.

As an exploratory effort, NHTSA conducted a quantifiable study of the relative locations of pedals in a limited set of passenger cars at its Vehicle Research and Test Center (VRTC) to determine whether elements of vehicle pedal design and location contribute to the propensity for pedal misapplication. Vehicles from populations of low and high rates of pedal misapplication were selected and dimensional variables as defined by an industry standard[1] were measured. Since it was the only source of such comprehensive information, including police accident report narratives, make and model information for pedal misapplication events were taken from the North Carolina State Crash Database. A NHTSA software program was used to define vehicle groups that were substantially similar based on factors such as brand, model, and vehicle wheelbase.[2] North Carolina vehicle registration records were used to limit the vehicles studied to passenger vehicle groups with over 100,000 model-years of exposure in the State with high misapplication rate (HMR) and low misapplication rate (LMR). Ten HMR models and 10 LMR models were selected for study. In addition, 12 models were selected for special interest, including vehicles with the highest exposure that did not fall in either of the previous groups, vehicles similar to HMR or LMR models with significantly different rates, and a vehicle that was the subject of a previous investigation into pedal misapplication.

Three vehicles of each model were located, and three-dimensional laser scans of the vehicle controls and surrounding area were obtained. These scans were converted into images from

[1] SAE J1100 Surface Vehicle Recommended Practice, "(R) Motor Vehicle Dimensions," Rev. 2009. Warrendale, PA: Society of Automotive Engineers.

[2] The program assigns a base code to a manufacturer's model platform. A new code is assigned when a change in wheelbase signals a change in the platform for the models.

which measurements were tabulated. The forces and displacements required to operate the accelerator and the brake pedal for each vehicle were also measured.

For this stage of the analysis, statistical correlation between the measured variables and the rate of pedal misapplication in the database was conducted but limited to only vehicle factors without including known demographic information. Stepover and accelerator position were the most correlated pedal dimensions to the rate. A number of variables describing vehicle size and/or the relation of the driver position to the vehicle controls showed moderate correlation. Products and ratios of the variables also indicated that many significant variables were related to driver seating position. No single variable had a high correlation to the misapplication rate.

Standard stepwise regression procedures were carried out to determine if there might be measurements that, when taken in combination, produced a high correlation to pedal misapplication. The model produced an R^2 value of 0.476. The most important pedal dimensions that showed some correlation were the stepover distance and the distance from the left edge of the brake to the vertical panel on the left. More notably, the ANOVA of the predicted rate for the LMR and HMR groups indicated that the model predicted rates were significantly different at $\alpha=0.05$ for the groups.

Previous work showed that driver characteristics such as age, gender, and height were correlated to the pedal misapplication rate in the North Carolina data.[3] At this point a second analysis was conducted in which driver demographic variables were added. The average age and height of drivers in the North Carolina data for each model were added to the analysis. Simply adding these variables to the previous model produced a slight increase in correlation. However, when the interactions of age and height with measured data were analyzed, a model with good agreement ($R^2 = 0.94$) between predicted and actual rates was found. The addition of this data inverted the correlation with stepover by indicating that higher stepover may be related specifically to higher pedal misapplication rates with older drivers. The two most important terms were the interaction between the average driver age for each vehicle and the stepover height, and the interaction between the average driver height and the separation between the brake and accelerator pedal. The effects of driver height and pedal separation predicted a generally higher rate for taller drivers when pedal separation became larger. In summary, both

[3] **Lococo, K. H., Staplin, L., Martell, C. A., & Sifrit, K. J. (2012).** *Pedal Application Errors.* (Report No. DOT HS 811 597). Washington, DC: National Highway Traffic Safety Administration.

the position of the vehicle controls and their estimated position relative to the seat position show some correlation with the pedal misapplication rate for vehicles in the data set. When taken in conjunction with average driver characteristics, these interactions are more strongly correlated to pedal misapplication, suggesting that optimal pedal dimensions for one demographic may not be optimal for another. While the analyses of this study have provided insights, pedal misapplication continues to be a difficult problem with no apparent optimization, and other data sets such as the North Carolina database do not exist to allow further assessment.

1.0 INTRODUCTION

After a 2010 study of the phenomenon of unintended acceleration (UA), the National Highway Traffic Safety Administration found that pedal misapplication could be a cause of many UA claims, specifically occurring when drivers intend to apply the brake but instead apply the accelerator, which can result in unintended acceleration of a vehicle. Consequently, NHTSA developed a research plan to determine whether elements of vehicle pedal design and location may contribute to the propensity for pedal misapplication. This research analysis was performed at NHTSA's Vehicle Research and Test Center (VRTC), and the goal was to conduct a quantifiable study of the relative locations of pedals in passenger cars to determine whether elements of vehicle pedal design and location contribute to pedal misapplication events.

Previous research efforts into UA events hypothesized that pedal design certain design criteria may contribute to the propensity for driver pedal error. An example of a design factor is "lateral separation," the horizontal gap between the brake and accelerator pedals. Another example is "stepover," the distance between the surface plane of the brake pedal and the surface plane of the accelerator pedal.

The objective of this exploratory study was to identify, then divide groups of vehicle models into two different populations based on either high or low reported rates of pedal misapplication events. After establishing the groups of models associated with high and low rates, similar models within the same generation of body style were sought to measure the brake and accelerator pedal geometry as defined by industry standard dimensional variables within the driver's space. After statistically analyzing the dimensions, a mathematical model was generated to correlate variables to rates of pedal misapplication.

2.0 BACKGROUND DISCUSSION

A UA event is defined as any unintended powered acceleration of a motor vehicle. That is, acceleration powered by the engine and not intentionally commanded by the operator via the vehicle's controls. UA events include, but are not limited to, stuck throttle, engine surging, high idle speed, and sudden acceleration incidents (SAI).

An SAI is defined in the report "An Examination of Sudden Acceleration"[4] as any "unintended, unexpected, high-power accelerations from a stationary position or very low initial speed accompanied by an apparent loss of braking effectiveness." The report was the result of a study conducted in the late 1980s to identify and evaluate factors that contribute to the occurrence of SAI. It also identified vehicle design factors such as pedal placement and pedal feedback as important variables in events that involve the unintentional misapplication of vehicle control pedals. This work indicated that a small lateral separation between the pedals is a design factor that can increase the probability of experiencing a UA event. Closely spaced brake and accelerator pedals can allow the width of the driver's foot to bridge across both pedals and cause dual application.

Another relevant design factor is stepover height, defined as the difference in height between the plane of the brake pedal face and the plane of the accelerator pedal face. Vehicles with little stepover height may cause the driver to inadvertently depress both pedals at the same time or be more likely to confuse the pedal location. In 1983, Audi recalled 117,000 Model 5000 passenger cars (Recall 83V-095[5]) due to insufficient stepover height and installed a brake pedal plate to increase the height of the pedal face.

Currently there is no globally accepted standard to regulate pedal placement, and significant variation can be found in the locations of pedal controls among vehicle manufacturers. Based on past research, it was hypothesized for this study that overall variability may be a contributing design factor in cases of UA events. It was also hypothesized that the forces required to operate both the brake and accelerator pedal may possibly be influential design factors. That is, if the force/displacement profiles of the brake and accelerator pedals are similar, the tactile feedback to the driver might cause a failure to properly identify the pedal being applied.

[4] Pollard, J., & Sussman, E. D. (1989, January) *An Examination of Sudden Acceleration*. (Report No. DOT HS 807 367). Washington, DC: National Highway Traffic Safety Administration. P. 1. Available at www.autosafety.org/sites/default/files/1989%20NHTSA%20SA%20Study%20Report%20&%20Appendices%20A-D(1).pdf

[5] NHTSA Campaign ID Number: 83V095000.

3.0 PRE INSPECTION DATA REVIEW

3.1 Data Selection

The data NHTSA used in this study contained records from the North Carolina State Crash Database. This data was selected because it uniquely offered detailed police accident report records, including narratives, with sufficiently specific vehicle make and model information for 2,411 UA incidents. This database was also recently used to study demographic information, which was presented in the NHTSA report "Pedal Application Errors."[6] The records covered a 5-year period from 2004 to 2008.

3.2 NHTSA Data Preparation

The vehicle identification number (VIN) data from the North Carolina database was processed with a series of software programs previously developed by NHTSA staff.[7] This software assigns code numbers based on information encoded in the VIN. The program identifies the vehicle's make, model, model year (MY), general body type, and wheelbase. The software assigns two codes based on this information; one is make-model code, and the other is a fundamental vehicle group code. A make-model code refers to a specific make and model of vehicle. A fundamental vehicle group code contains all of a manufacturer's models of the same type having the same wheelbase and can cover several model years. The software uses the change in vehicle wheelbase as an indicator of vehicle design change to assign codes.

To refine the data to repeatable wheelbase codes, NHTSA removed all reports assigned a fundamental vehicle group code indicating the vehicle was a truck, van, or sport utility vehicle because (1) dimensional values are characteristically larger than the same variables in automobiles, likely producing two distinct distributions of values and (2) SUV options are

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[6] Lococo, Staplin, Martell, & Sifrit, 2012.

[7] Kahane, C. J. (1994, January). *Correlation of NCAP performance with fatality risk in actual head-on collisions*. (Report No. DOT HS 808 061). Washington, DC: National Highway Traffic Safety Administration. Pp. 18-19. Available at www-nrd.nhtsa.dot.gov/Pubs/808061.PDF

and

Kahane, C. J. (1997, January). *Relationships between vehicle size and fatality risk in model year 1985-93 passenger cars and light trucks.* (Report No. DOT HS 808 570). Washington, DC: National Highway Traffic Safety Administration. Pp. 15-17. Available at www-nrd.nhtsa.dot.gov/Pubs/808570.pdf generally more customizable, leading to multiple wheelbases associated with the same vehicles. This resulted in 871 reports from the North Carolina database being removed for this study.

NHTSA double sorted the remaining 1,540 passenger car reports by the assigned make model code first and then by the fundamental vehicle group code. NHTSA summed the number of UA events and the number of registration years for each make/model group within a fundamental vehicle code. The rate of UA events for every 100,000 registration years was calculated for each make and model. This rate was used to identify the make model codes with the lowest and highest rates of UA. The 10 codes with the lowest rates were identified as the Lowest Misapplication Rates (LMR) and are listed in Table 1. The 10 codes with the highest rates were identified as the Highest Misapplication Rates (HMR) and are listed in Table 2. Another 12 make model group codes including the code for the 1985 Audi 5000S (subject of the 1987 investigation[8]) were included as codes of special interest and are shown in Table 3.

[8] Pearse, D. (1987).. *Inspection and Testing of a 1985 Audi 5000S for Surprise Acceleration*. (Report No. VRTC-7-6-0049A). Washington, DC: National Highway Traffic Safety Administration. Cited in some documents as: U.S. Department of Transportation. National Highway Traffic Safety Administration. Vehicle Research and Test Center. Inspection and Testing of a 1985 Audi 5000S for Surprise Acceleration, by Daniel Pearse. East Liberty, OH: VRTC, 1987.

LMR			
YEAR	MAKE	MODEL	VIN
1997-2008 Pontiac Grand Prix			
1999	Pontiac	Grand Prix	1G2WP12K9XFXXXXXX
1999	Pontiac	Grand Prix	1G2WP52K5XFXXXXXX
2004	Pontiac	Grand Prix	2G2WR524041XXXXXX
2008	Pontiac	Grand Prix	2G2WP552781XXXXXX
2002-2008 Nissan Altima			
2003	Nissan	Altima	1N4AL11D43CXXXXXX
2007	Nissan	Altima	1N4BL21E77CXXXXXX
2007	Nissan	Altima	1N4AL21E67CXXXXXX
1994-2004 Ford Mustang			
1998	Ford	Mustang	1FAFP42X3WFXXXXXX
2002	Ford	Mustang	1FAFP40412FXXXXXX
2004	Ford	Mustang	1FAFP44684FXXXXXX
1983-1991 Toyota Camry			
1987	Toyota	Camry	JT2SV21E3H3XXXXXX
1990	Toyota	Camry	JT2VV22W2L0XXXXXX
1991	Toyota	Camry	JT2SV21E7M3XXXXXX
1984-1999 Oldsmobile Delta88			
1991	Olds	Delta 88	1G3HN54C1MHXXXXXX
1993	Olds	88 Royale	1G3HN53L5P1XXXXXX
1999	Olds	88	1G3HC52K5X4XXXXXX
1991-2002 Saturn SL			
2001	Saturn	SL1	1G8ZH52891ZXXXXXX
2002	Saturn	SL	1G8ZK52782ZXXXXXX
2002	Saturn	SL1	1G8ZH52832ZXXXXXX
1979-1993 Ford Mustang			
1988	Ford	Mustang	1FABP45E1JFXXXXXX
1991	Ford	Mustang	1FACP42E4MFXXXXXX
1993	Ford	Mustang	1FACP42EBPFXXXXXX
1994-1999 Cadillac DeVille			
1995	Cadillac	Deville	1G6KD52B6SUXXXXXX
1998	Cadillac	Deville	1G6KD54Y9WUXXXXXX
1999	Cadillac	Deville	1G6KD54Y3XUXXXXXX
1982-2002 Chevrolet Camaro			
1987	Chevrolet	Camaro	1G1FP21S3HNXXXXXX
1989	Chevrolet	Camaro	1G1FP21E8KLXXXXXX
1989	Chevrolet	Camaro	1G1FP21EXKLXXXXXX
1994	Chevrolet	Camaro	2G1FP32P3R2XXXXXX
2000	Chevrolet	Camaro	2G1FP22G9Y2XXXXXX
2002	Chevrolet	Camaro	2G1FP22G222XXXXXX
1997-2008 Chevrolet Impala/Caprice			
2003	Chevrolet	Impala	2G1WF52E539XXXXXX
2005	Chevrolet	Impala	2G1WF52E359XXXXXX
2007	Chevrolet	Impala	2G1WT58K379XXXXXX

Table 1 Lowest Misapplication Rates (LMR)

HMR			
YEAR	MAKE	MODEL	VIN
1992-2008 Mercury Grand Maquis			
1995	Mercury	Grand Marquis	2MELM74W3SXXXXXXX
2006	Mercury	Grand Maquis	2MEFM75W86XXXXXXX
2008	Mercury	Grand Marquis	2MEFM75V58XXXXXXX
2002-2006 Toyota Camry			
2003	Toyota	Camry	4T1BE30KX3UXXXXXX
2004	Toyota	Camry	4T1BE32K14UXXXXXX
2005	Toyota	Camry	4T1BE32K35UXXXXXX
1994-2005 Mitsubishi Galant			
2000	Mitsubishi	Galant	4A3AA46G9YEXXXXXX
2003	Mitsubishi	Galant	4A3AA46H33EXXXXXX
2005	Mitsubishi	Galant	4A3AB36F45EXXXXXX
1993-2001 Toyota Corolla			
2000	Toyota	Corolla	2T1BR12E9YCXXXXXX
2000	Toyota	Corolla	2T1BR12E1YCXXXXXX
2001	Toyota	Corolla	1NXBR12E91ZXXXXXX
2003-2008 Toyota Corolla			
2003	Toyota	Corolla	1NXBR32E53ZXXXXXX
2007	Toyota	Corolla	2T1BR32E07CXXXXXX
2007	Toyota	Corolla	2T1BR32E17CXXXXXX
1993-2001 Nissan Altima			
1994	Nissan	Altima	1N4BU31D0RCXXXXXX
2001	Nissan	Altima	1N4DL01D31CXXXXXX
2001	Nissan	Altima	1N4DL01D21CXXXXXX
1995-2006 Dodge Stratus			
1999	Dodge	Stratus	1B3EJ46X9XNXXXXXX
2004	Dodge	Stratus	4B3AG42G44EXXXXXX
2006	Dodge	Stratus	1B3EL46X06NXXXXXX
1986-1995 Ford Taurus			
1994	Ford	Taurus	1FALP52U5RAXXXXXX
1995	Ford	Taurus	1FALP52U5SAXXXXXX
1995	Ford	Taurus	1FALP52U4SAXXXXXX
1995-2006 Nissan Sentra			
2002	Nissan	Sentra	3N1CB51D32LXXXXXX
2004	Nissan	Sentra	3N1CB51D04LXXXXXX
2006	Nissan	Sentra	3N1CB51D16LXXXXXX
1995-2004 Toyota Avalon			
1995	Toyota	Avalon	4T1GB11E5SUXXXXXX
1997	Toyoya	Avalon	4T1BF12B8VUXXXXXX
2000	Toyota	Avalon	4T1BF28B6YUXXXXXX

Table 2: Highest Misapplication Rates (HMR)

Special Interest Vehicles				
Make	Model	Model Years	Rate, Incidents / 100,000 Vehicle-Year	Comment
HONDA	ACCORD	1994	9.8	High number of total incidents (67)
HONDA	ACCORD	1999		
HONDA	ACCORD	2003		
HONDA	CIVIC	1992	7.1	High number of total incidents (36) and comparison to similar cars
HONDA	CIVIC	1997		
HONDA	CIVIC	2005		
FORD	CROWN VICTORIA	1979-2008	8.7	Lower rate than Mercury Grand Marquis (8.7 versus 20.2 /100,000 vehicle-years)
CADILLAC	STS	2005	32.6	High rate per 100,000 vehicle-years
CADILLAC	STS	2008		
CADILLAC	CTS	2003-2008	3.6	Same platform as STS with lower rate
AUDI	5000S	1985	-	Previous history of pedal misapplications

Table 3 List of Special Interest Vehicles

3.3 Data Preparation

To further focus the data on vehicle design characteristics, NHTSA audited the narratives found in the North Carolina database. NHTSA removed all records involving events where the narrative indicated circumstances that cast doubt on the occurrence being a genuine pedal misapplication. This excluded cases involving physical impairment of the driver such as: drugs, alcohol, or a driver's leg being in a cast. Also excluded were cases of underage or unlicensed drivers, narratives which indicated the driver was inexperienced, and one situation where the driver jumped into a moving vehicle. Removal of these cases reduced the test data by 110 records, leaving 1,430 records for analysis.

NHTSA also audited the fundamental vehicle group code data and found that the codes did not account for manual transmissions, a limitation in the data analysis. The codes, based on wheelbase, were not always coincident with technological changes in vehicle design. An example of a technological change is when a manufacturer changed from a mechanical accelerator pedal linkage to electronic throttle control (ETC) while not changing the wheelbase. It was important to distinguish technological changes not only because system functionality changed, but also because the new equipment (accelerator pedal) was physically different in shape, location, and actuation. For situations where this change occurred, the rates were recalculated and compared to their overall rank. In no case did this remove any vehicle from the list of the highest or lowest pedal misapplication rate vehicles.

For example, in the review of the fundamental vehicle group code 18049 (General Motors F-body 101, 1982-2002), an extensive redesign of the vehicle occurred between MY 1992 and MY 1993, while the fundamental vehicle group code did not change. NHTSA studied the two generations of vehicles separately and determined that they remained sufficiently similar with respect to pedal locations, shapes, and actuation to remain combined in one group. This decision was reinforced by data suggesting the pedal misapplication rates between the two were substantially similar.

4.0 VEHICLE INSPECTION AND DATA COLLECTION

NHTSA located 3 vehicles for each of the 32 make model/fundamental vehicle group combinations (10 LMR, 10 HMR, and 12 Special Interest). Two of the groups included additional vehicles, and resulted in inspecting and collecting data on a total of 101 vehicles (Appendix A shows a complete list).

Each vehicle was inspected to ensure its compliance to the following items:

1. The make, model, and model year of the vehicle corresponded to the Fundamental Vehicle Group (FVG).
2. The vehicle started and the accelerator functioned properly.
3. The vehicle's brake system functioned with no signs of leakage.

Two primary areas of data collection were required for this project. The first was a three-dimensional (3D) laser scan of the vehicle controls and surrounding area. The second was recording the force required to operate the vehicle's brake and accelerator pedals. A description of equipment used in each area is listed in Appendix B. In cases where vehicles failed to start, dimensional data for the pedals was still gathered, but brake and accelerator force tests were not conducted.

4.1 Three Dimensional Laser Scanning

The vehicle floor mats (if installed) were removed and reference targets placed arbitrarily around the driver's area. The driver's seat was positioned in the full rearward position. If the vehicle was equipped with a tilt steering column, it was set to the position closest to the center of the arc of travel. On vehicles equipped with adjustable pedals, both ends of the adjustment travel were scanned.

A hand-held 3D laser scanner was used to record the locations of the control pedals, driver's seat, and steering wheel. The scanner operates tethered to a computer, and the data gathered was stored in a standard stereo lithography (*.stl) file format. A typical session of data being recorded is shown in Figure 1. The operator would scan the vehicle surfaces until the computer rendering (Figure 2) showed that all required surfaces had been adequately covered. The accelerator pedal was scanned in three positions. The first was the static position, the second was the fully depressed wide open throttle position, and the third was a point of travel at the approximate center of the first two positions.

Figure 1 - Typical Scanning Session

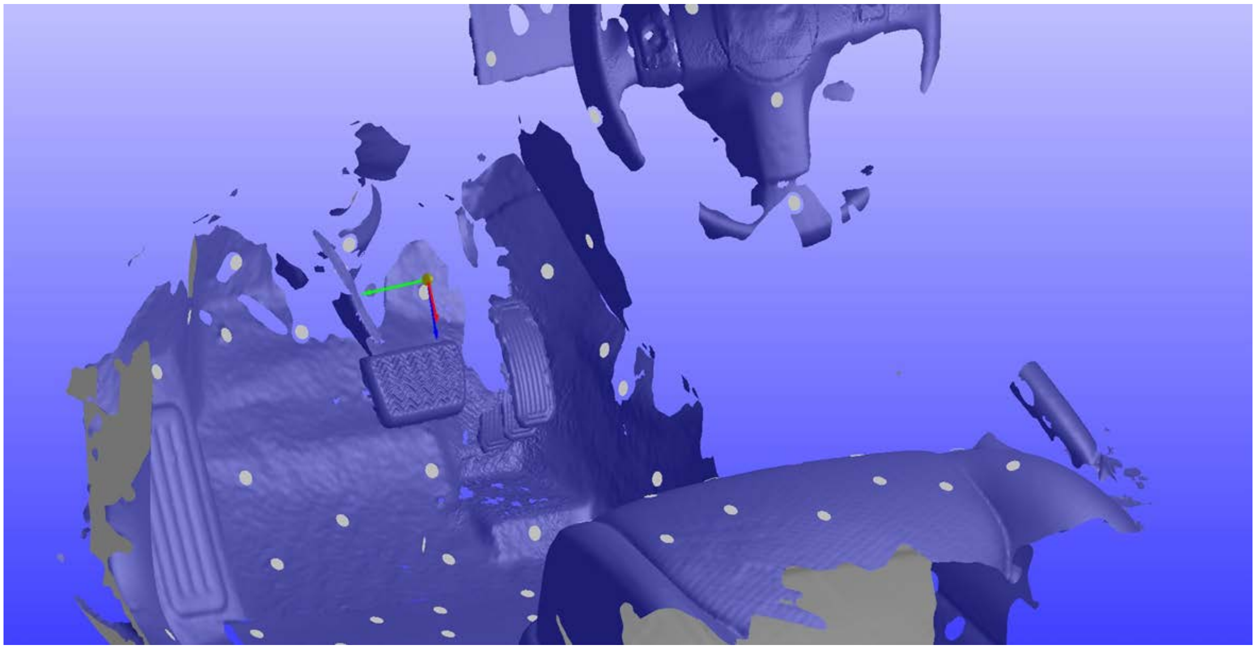

Figure 2 - Typical Screenshot of Computer Rendering

4.2 Pedal Force and Displacement Measurements

Pedal force and displacement measurements were taken for both the accelerator and brake pedals. The measuring device shown in Figure 3 included a force transducer with a working range of 0-50 pounds force and a linear potentiometer with a working range of 0 to 8 inches. The device was installed and aligned with the accelerator pedal. The position of the linear actuator was advanced until the device came into positive contact with the pedal, which occurred with between 1 and 2 pounds of applied force. This location was set as the starting position in the motor's control software, and the output of both the force transducer and the linear potentiometer were set to zero. The linear actuator was advanced until the force applied reached 15 pounds force in order to meet or exceed the most resistant pedal. This position was set as the hold position in the control software. The linear actuator was returned to the start position.

Figure 3 - Pedal Force and Displacement Measuring Device

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The data collection system was started and the motor's control software was used to record the data from three complete cycles. The data collection system was stopped, and the device was repositioned to the brake pedal to repeat the process. When testing the brake pedal, the vehicle was started and the throttle applied and released to allow sufficient vacuum to build in the brake booster. This allowed normal operation of the brake pedal.

5.0 CONTROL LOCATION MEASUREMENTS

NHTSA identified 21 variables, shown in Table 4, for which dimensional measurements were collected for analysis. Eighteen of these are identified in SAE J1100.[9] Three other measurements were defined by NHTSA and appear in the table as variables K, M, and U.

Variable Number	Letter Identifier	SAE Variable	Description
1	A	PW-17	Accelerator to tunnel
2	B	PW-21	Lateral spacing right edge of brake to left edge accel
3	C	PW-27	Right edge of brake to tunnel – horizontal
4	D	PW-42	Left edge of brake to vertical panel on left
5	E	PW-82	Brake CL to accel CL
6	F	PW-92	Driver CL to right edge of brake
7	G	PW-98	Driver CL to accel horizontal CL
8	H	PL-52	Stepover - brake to accel -shortest arc distance
9	I	PH-26	Bottom edge of brake pedal to undepressed floor
10	J	PH-16	Bottom edge of accel pedal to undepressed floor
11	K	SAE(not identified)	Seat anchor center to steering center
12	L	SW-16	Seat cushion width
13	M	SAE(not identified)	Steering centerline to brake pedal center
14	N	PL-1	Stepover in shoe plane
15	O	PW-47	Overall width of floorpan @ 150 mm above floor
16	P	H-17	Height of steering wheel from floor
17	Q	W-9	Width of steering wheel
18	R	L-6	Ball of foot accel pedal to front center of steering wheel
19	S	PW-22	Brake Pedal Width
20	T	PW-11	Accel Pedal Width
21	U	SAE(not identified)	Arc Length of Accelerator Pedal

Table 4 - List of Dimensions Analyzed

The data acquired by the 3D laser scan of the vehicle's driver controls was analyzed in a computer aided design (CAD) software program. The program allowed the 3D rendering of the vehicle to be rotated to the optimal viewing angle and measurements taken. A table of all measurement results can be found in Appendix C. NHTSA identified five views displaying the measurement results for each vehicle, and Figure 4 shows a typical image from the first view. A complete set of images for each vehicle can be found in Appendix D.

[9] SAE J1100, 2009.

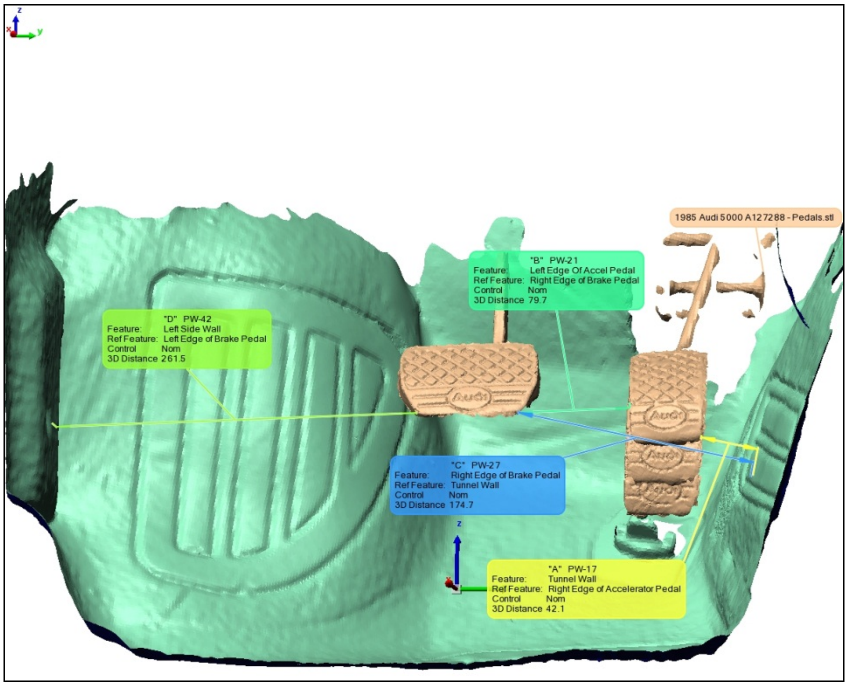

Figure 4- Typical View the 3D Rendering Used for Variables A, B, C, and D Showing the Accelerator Travel Path

6.0 DATA ANALYSIS

6.1 LMR/HMR Groups

As discussed previously, the LMR and HMR groups were selected as the vehicles with the lowest and highest rates of pedal misapplications per 100,000 vehicles. To verify that these vehicles represented distinct groups, the pedal misapplication rate (hereafter rate) for the groups, as well as the rates for the Special Interest group, were analyzed using the general linear model (GLM) procedure of the SAS statistical analysis software, to evaluate a one-way ANOVA at $\alpha=0.05$ using Scheffe's test for significance. This analysis was limited to only vehicle dimensions. The groups had significantly different rates as shown in Figure 5. All data is shown in Appendix F.

Group Comparison	Difference Between Means	Simultaneous 95% Confidence Limits		
HMR - LMR	**10.0134**	**8.7018**	**11.3250**	***
Special - HMR	**-4.4345**	**-5.8577**	**-3.0114**	***
Special - LMR	**5.5788**	**4.1647**	**6.9929**	***

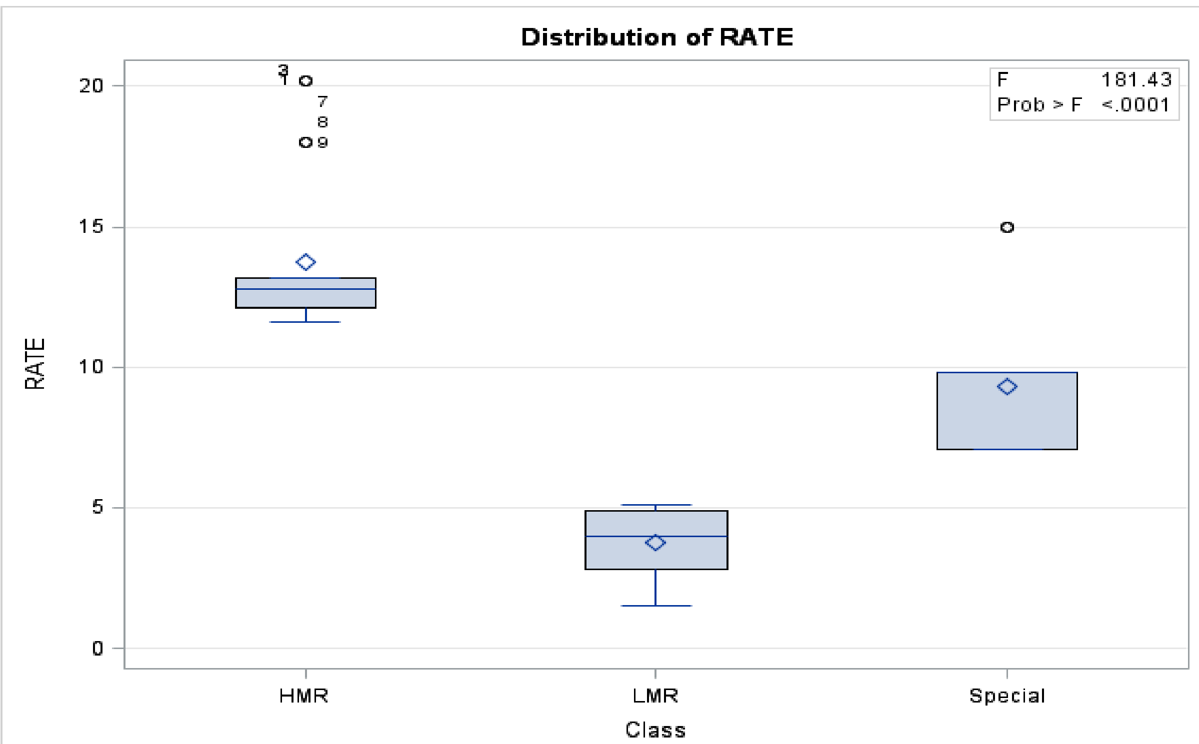

Figure 5 - ANOVA for Difference Between LMR, HMR and Special Interest Rates of Pedal Misapplication

6.2 Correlation of Measured Variables

The variables measured for each vehicle are listed in Table 5. The Pearson product-moment correlation (r-value) of the variables' correlation to one another was analyzed. A positive r-value indicates a direct correlation and a negative value indicates an inverse correlation. The strength of the correlation is described by the absolute value from 0 (no correlation) to ±1.0 (exact correlation). Variables with a statistically significant correlation at α=0.05 are shown in Table 6. Variables F and N were eliminated since they are comparable to variables G and H, respectively. Variable O (overall width of the floor pan) is the sum of the distances that comprise it. Although correlated to many variables, Variable O was retained because the ratios of the individual distances to the overall width were of interest. Variable C was eliminated since it can be described as a function of other variables. The remaining 18 variables were investigated to determine correlation to the observed rate.

Variable Number	Letter Identifier	SAE Variable	Description
1	A	PW-17	Accelerator to tunnel
2	B	PW-21	Lateral spacing right edge of brake to left edge accel
3	**C**	**PW-27**	**Right edge of brake to tunnel – horizontal**
4	D	PW-42	Left edge of brake to vertical panel on left
5	E	PW-82	Brake CL to accel CL
6	**F**	**PW-92**	**Driver CL to right edge of brake**
7	G	PW-98	Driver CL to accel horizontal CL
8	H	PL-52	Stepover - brake to accel -shortest arc distance
9	I	PH-26	Bottom edge of brake pedal to undepressed floor
10	J	PH-16	Bottom edge of accel pedal to undepressed floor
11	K	SAE(not	Seat anchor center to steering center
12	L	SW-16	Seat cushion width
13	M	SAE(not	Steering centerline to brake pedal center
14	**N**	**PL-1**	**Stepover in shoe plane**
15	O	PW-47	Overall width of floorpan @ 150 mm above floor
16	P	H-17	Height of steering wheel from floor
17	Q	W-9	Width of steering wheel
18	R	L-6	Ball of foot accel pedal to front center of steering wheel
19	S	PW-22	Brake Pedal Width
20	T	PW-11	Accel Pedal Width
21	U	identified)	Arc Length of Accelerator Pedal

Table 5 - Pedal Dimensions Measured, Variables Shown in Bold Eliminated From Analyses

Variable1	Variable2	Correlation	Variable1	Variable2
F	G	0.9	Driver CL to Right Edge of Brake	Driver CL to accel horizontal CL
H	N	0.88	Stepover - brake to accel - shortest arc distance	Stepover in shoe plane
C	O	0.71	Right of brake to tunnel - horizontal	Overall width of floor pan @150 mm above floor
A	C	0.66	Accelerator to Tunnel	Right of brake to tunnel - horizontal
E	S	0.65	Brake CL to accel CL	Brake Pedal Width
D	O	0.57	Left edge of brake to vertical panel on left	Overall width of floor pan @150 mm above floor
H	R	0.57	Stepover - brake to accel - shortest arc distance	Ball of foot accel to front center of steering wheel
B	O	-0.54	Right edge of Brake to left edge of accel (arc)	Overall width of floor pan @150 mm above floor
F	M	-0.54	Driver CL to Right Edge of Brake	Steering CL to Brake Pedal center
P	R	-0.54	Height of steering wheel from floor	Ball of foot accel to front center of steering wheel
A	O	0.52	Accelerator to Tunnel	Overall width of floor pan @150 mm above floor
E	G	0.52	Brake CL to accel CL	Driver CL to accel horizontal CL
O	S	0.52	Width of floor pan @150mm above floor	Brake Pedal Width
N	R	0.51	Stepover in shoe plane	Ball of foot accel to front center of steering wheel
O	T	0.51	Width of floor pan @150mm above floor	Accel pedal width

Table 6 - Correlation of Measured Variables to Each Other

6.3 Correlation of Variables to Pedal Misapplication Rate

Six of the 18 remaining variables had statistically significant correlations to the rate of pedal misapplication as shown in Table 7. The measured values of each value for the LMR and HMR group were compared using a one-way ANOVA. For all of the variables, there was a significant difference between the groups at α=0.05. The means for the values in each group are shown in Table 7. There was no strong correlation (|r| >0.5) for any of the measured variables. The values for all of these variables however, were statistically different for the LMR and HMR groups. Variables Q (width of steering wheel) and L (seat cushion width) are not directly correlated to pedal measurements. The initial assumption was that these related to the size of the vehicle.

Variable	Description	Correlation, r	Probability >|r|	Mean for LMR Group	Mean for HMR Group	Probability >|t|
Q	Width of steering wheel	-0.29386	0.0063	384.4	379.9	0.0125
H	Stepover - brake to accel - shortest arc distance	-0.28996	0.0068	56.1	48.4	0.0033
A	Accelerator to tunnel	0.26723	0.0129	36.4	45.8	0.0182
L	Seat cushion width	0.25688	0.0176	525.4	543.8	0.0483
D	Left edge of brake to vertical panel on left	-0.21724	0.0445	246.1	234	0.05
I	Bottom edge of brake pedal to undepressed floor	0.20429	0.0491	148.16	157.18	0.0473

Table 7 - Correlation of Measured Variables to Pedal Misapplication Rate

The rate was compared to the square of the measured value to investigate whether there might be a relationship to a maximum or minimum value. The results are shown in Table 8. Four variables with the most previous significant correlation had similar correlations as squared terms. The correlation was no greater, indicating that an optimum value in the range measured was unlikely. While the stepover had an inverse correlation to the misapplication rate (smaller stepover correlated to higher rates), the significance of the square term indicates that higher rates would correlate to both very low and very high stepover distances.

Term	Description	Corelation, r	Probability > |r|
Q^2	Width of steering wheel	-0.29865	0.0055
H^2	Stepover - brake to accel - shortest arc distance	-0.29064	0.0066
L^2	Seat cushion width	0.26638	0.0137
A^2	Accelerator to tunnel	0.244	0.0236

Table 8 - Correlation of (Measured Variables) Squared to Pedal Misapplication Rate

The next step was to investigate whether the interaction of any two variables correlated to the misapplication rate. The correlation of all 2-variable products measured for each vehicle was compared to the rate, and the results for all correlations significant at α=0.01 are shown in Table 9. An α of 0.01 was chosen to represent similar confidence to an α of 0.05 for a single variable. The correlation is somewhat higher, but there are still no strong correlations, and most of the variables are the same as those with a direct correlation. An interesting observation was that many of the most significant products were combinations of pedal measurement and another measurement of the vehicle, such as the distance from the driver's centerline to the accelerator pedal horizontal centerline. There was not sufficient data to consider any interactions beyond two-way interactions.

Product of Var1	Product of Var2	Description 1	Description 2	Correlation, r	Probablity >|r|
G	H	Driver CL to Accel Horizontal CL	Stepover – brake to accel – shortest distance	-0.39268	0.0002
I	Q	Bottom edge of brake pedal to undepressed floor	Width of steering wheel	0.34127	0.0014
D	G	Left edge of brake to vertical panel on left	Driver CL to Accel Horizontal CL	-0.33062	0.0019
A	B	Accelerator to Tunnel	Lateral right edge brake to left edge accel - arc	0.31185	0.0035
H	Q	Stepover – brake to accel – shortest distance	Width of steering wheel	-0.31263	0.0036
H	J	Stepover – brake to accel – shortest distance	Bottom edge of accel pedal to undepressed floor	-0.30994	0.0039
A	L	Accelerator to Tunnel	Seat cushion width	0.30401	0.0047
B	H	Lateral right edge brake to left edge accel - arc	Stepover – brake to accel – shortest distance	-0.29609	0.0056
H	P	Stepover – brake to accel – shortest distance	Height of steering wheel from floor	-0.27879	0.0093
A	I	Accelerator to Tunnel	Bottom edge of brake pedal to undepressed floor	0.27762	0.0097
E	H	Brake CL to accel CL	Stepover – brake to accel – shortest distance	-0.27698	0.0098

Table 9 - Correlation of Products of Measured Variables to Pedal Misapplication Rate

It was theorized that the ratio of some variables might be significant. The ratios of all variables were investigated for correlation at α=0.01, and the results are shown in Table 10. Variable 1 is first alphabetically, and the inverse of every ratio was not directly compared. As with the products, there are somewhat better correlations and the variables are primarily the same as those with direct comparisons.

Ratio of Var1	Ratio of Var2	Description 1	Description 2	Correlation, r	Probability >|r|
A	G	Accelerator to Tunnel	Driver CL to Accel Horizontal CL	0.37064	0.0004
H	L	Stepover – brake to accel – shortest distance	Seat cushion width	-0.37337	0.0004
H	I	Stepover – brake to accel – shortest distance	Bottom edge of brake pedal to undepressed floor	-0.36143	0.0006
A	H	Accelerator to Tunnel	Stepover – brake to accel – shortest distance	0.34231	0.0013
A	D	Accelerator to Tunnel	Left edge of brake to vertical panel on left	0.32546	0.0022
L	Q	Seat cushion width	Width of steering wheel	0.32503	0.0026
H	O	Stepover – brake to accel – shortest distance	Overall width of floor pan @150 mm above floor	-0.31501	0.0031
A	J	Accelerator to Tunnel	Bottom edge of accel pedal to undepressed floor	0.29718	0.0057
A	O	Accelerator to Tunnel	Overall width of floor pan @150 mm above floor	0.29464	0.0059
D	I	Left edge of brake to vertical panel on left	Bottom edge of brake pedal to undepressed floor	-0.29	0.0068
H	P	Stepover – brake to accel – shortest distance	Height of steering wheel from floor	-0.28999	0.0068

Table 10 - Correlation of Ratios of Measured Variables to Pedal Misapplication Rate

6.4 Regression Analysis

The correlation analyses, limited to only vehicle dimensions, showed that while there were variables with moderate correlation to the misapplication rate, no single variable or interactions had a strong correlation to the rate. Accordingly, standard stepwise regression techniques were used to investigate the possibility that some combination of variables might be important correlates to the rate.

Due to the large number of variables, the use of regression techniques are known to have a high Type I error and should not be construed as an attempt to define an equation for the predicted rate (i.e. a response surface) from the data. Rather, it is an attempt to define what variables are most important. Three datasets were generated as a baseline to simulate a random central value with a random-normal distribution of three values per vehicle per dimension. These were then evaluated using stepwise regression. The highest model R^2 value found was 0.115 and the greatest number of significant variables at $\alpha=0.05$ was 4 terms.

The stepwise regression of measured variables significant at $\alpha=0.05$ is shown in Table 11. As expected, most of the significant variables are the ones with significant correlation to the rate. No term has a strong effect, and the overall R^2 of 0.36 indicates that there is a general relationship between the variables and the rates. The earlier assumption that the width of the steering wheel and the width of the seat cushion may be related to some other aspect, such as the overall size of the car, is reinforced by the fact that the stepwise regression does not include both terms.

Step	Variable Entered	Partial R-Square	Model R-Square	F Value	Pr > F
1	Stepover – brake to accel – shortest distance	0.0897	0.0897	8.58	0.0043
2	Driver CL to Accel Horizontal CL	0.0851	0.1749	8.87	0.0038
3	Seat cushion width	0.0818	0.2567	9.36	0.003
4	Accelerator to FC steering wheel	0.0573	0.314	7.02	0.0096
5	Bottom edge of brake pedal to undepressed floor	0.0461	0.3602	5.99	0.0165

Table 11 - Regression Analysis: Pedal Misapplication Rate Versus Measured Dimensions

Regression analysis of the terms plus their values squared produced similar results to the analysis without the squared terms as shown in Table 12.

Step	Variable Entered	Partial R-Square	Model R-Square	F Value	Pr > F
1	Stepover – brake to accel – shortest distance	0.0897	0.0897	8.58	0.0043
2	Driver CL to Accel Horizontal CL	0.0851	0.1749	8.87	0.0038
3	Seat cushion width	0.0818	0.2567	9.36	0.003
4	Bottom edge of brake pedal to undepressed floor	0.0491	0.3058	5.94	0.0169
5	$(\text{Bottom edge of brake pedal to undepressed floor})^2$	0.0494	0.3552	0.36	0.0136
6	$(\text{Right edge of brake pedal to tunnel})^2$	0.0392	0.3943	5.3	0.0238

Table 12 - Regression Analysis: Pedal Misapplication Rate Versus Measured Dimensions and Dimensions Squared

The regression analyses for the variables and all products of two variables and for all ratios of two variables are shown in Table 13 and Table 14, respectively. The variables that showed correlation were retained in the regression indicating that the effects are statistically independent (i.e. additive).

Step	Interaction of		Partial	Model	F Value	Pr > F
	Variable 1	Variable 2	R-Square	R-Square		
1	Driver CL to Accel Horizontal CL	Stepover – brake to accel – shortest distance	0.1758	0.1758	19.2	<.0001
2	Seat cushion width	Height of steering wheel from floor	0.1226	0.2984	15.55	0.0002
3	Width of steering wheel	Ball of foot accel pedal to FC of steering wheel	0.0483	0.3468	6.51	0.0124
4	Bottom edge of brake pedal to undepressed floor	Seat cushion width	0.0447	0.3915	6.39	0.0133

Table 13 - Regression Analysis: Pedal Misapplication Rate Versus Measured Dimensions and Two-way Products of Variables

Step	Ratio of		Partial	Model	F Value	Pr > F
	Variable 1	Variable 2	R-Square	R-Square		
1	Accelerator to tunnel	Driver CL to Accel Horizontal CL	0.1477	0.1477	15.6	0.0002
2	Stepover – brake to accel – shortest distance	Bottom edge of brake pedal to undepressed floor	0.1442	0.2919	18.13	<.0001
3	Bottom edge of accelerator pedal to undepressed floor	Ball of foot accel pedal to FC of steering wheel	0.0466	0.3386	6.2	0.0146
4	Stepover – brake to accel – shortest distance	Height of steering wheel from floor	0.0391	0.3776	5.46	0.0218
5	Width of steering wheel		0.038	0.4156	5.6	0.0202

Table 14 - Regression Analysis: Pedal Misapplication Rate Versus Measured Dimensions and Two-Way Ratios of Variables

A stepwise regression analysis was performed using all measured values, their squares, all two-way interactions of values, and all two-way ratios of values. The results are shown Table

15. Most of the significant terms are not directly pedal measurements, but are measurements relative to potential driver seating position or are interactions with driver position and pedal measurements. The most significant pedal dimensions are the stepover distance (H) and the distance from the left edge of the brake to the vertical panel on the left (D). The predicted rate from the regression versus the measured rate for each individual vehicle is shown in Figure 6. The error term was normally distributed as shown in Figure 7. More significantly, the ANOVA of the predicted rate for the LMR and HMR groups, shown in Figure 8, indicates that a combination of measured variables produces distinctly different predicted rates for the LMR and HMR groups of vehicles measured in this study.

Step	Description	Variable 1	Variable 2	Partial R-Square	Model R-Square	F Value	Pr > F
1	Interaction of	Driver CL to Accel Horizontal CL	Stepover – brake to accel – shortest distance	0.1758	0.1758	19.2	<.0001
2	Ratio of	Seat cushion width	Ball of foot accel pedal to FC of steering wheel	0.1462	0.3221	19.2	<.0001
3	Ratio of	Bottom edge of brake pedal to undepressed floor	Width of steering wheel	0.0622	0.3843	8.89	0.0037
4	Left edge of brake to vertical panel on left			0.0244	0.4087	3.59	0.0493
6	(Width of steering wheel)^2			0.0673	0.476	11.6	0.001

Table 15- Regression Analysis: Pedal Misapplication Rate Versus Measured Dimensions, Dimensions Squared, Two-Way Interactions, and Ratios of Variables

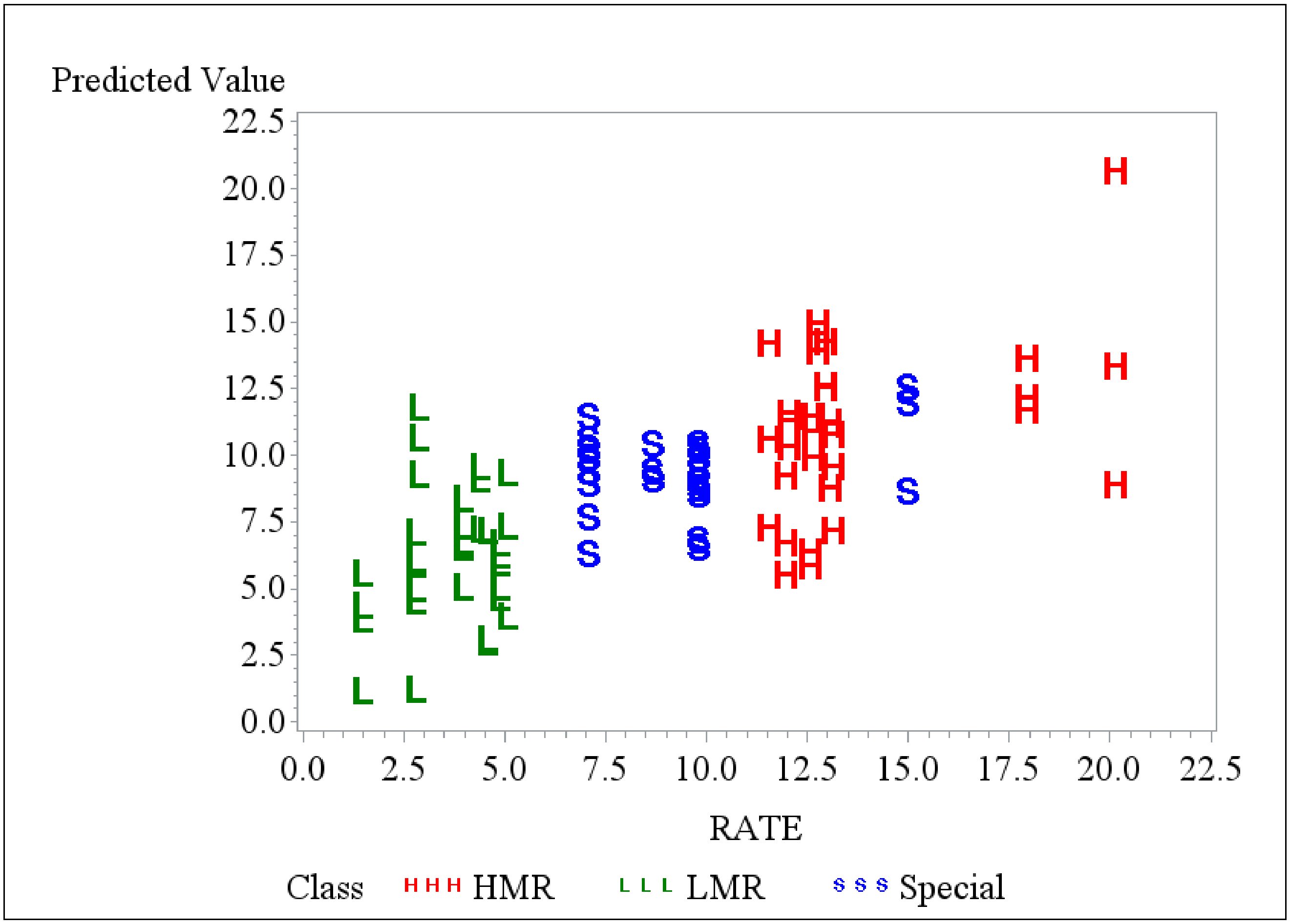

Figure 6 - Predicted Value Versus Measured Rate of Pedal Misapplication for Vehicles: L = LMR, S = Special Interest, H = HMR Groups

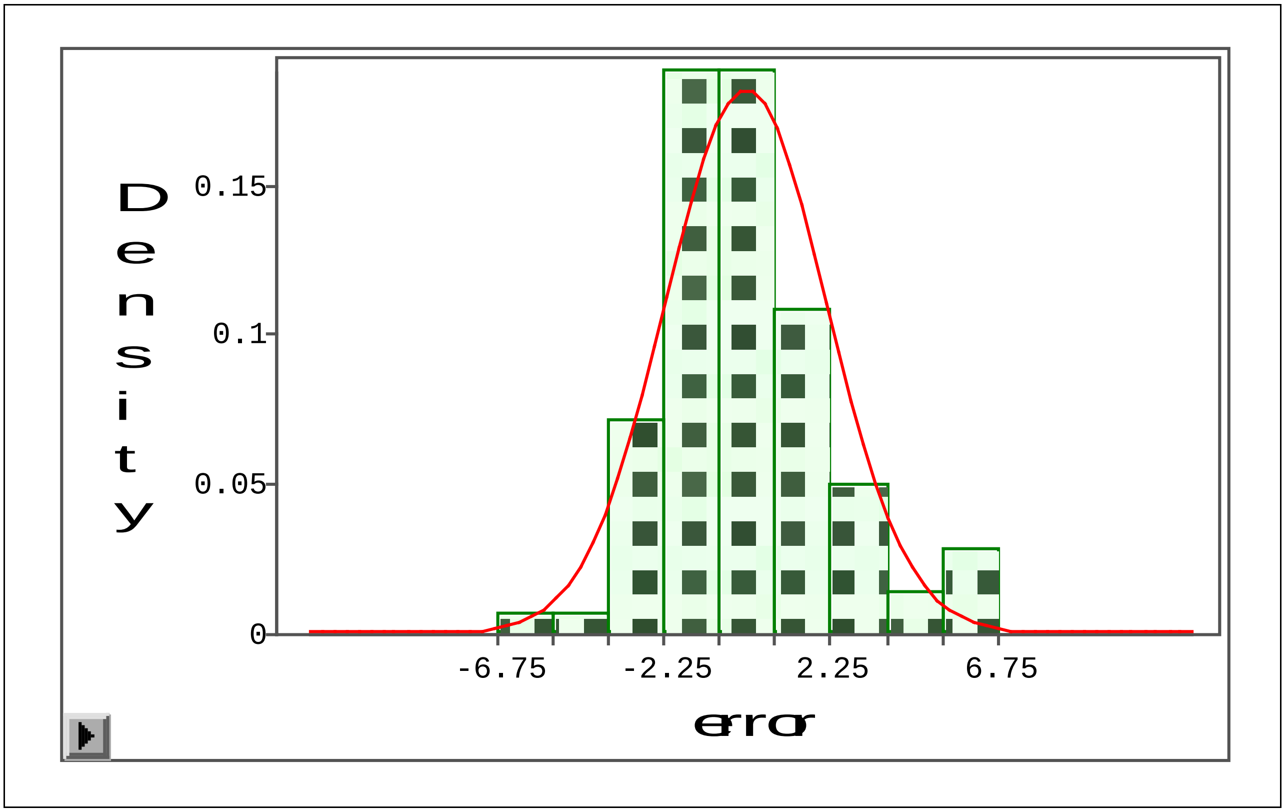

Figure 7 - Distribution of Error Term From Regression

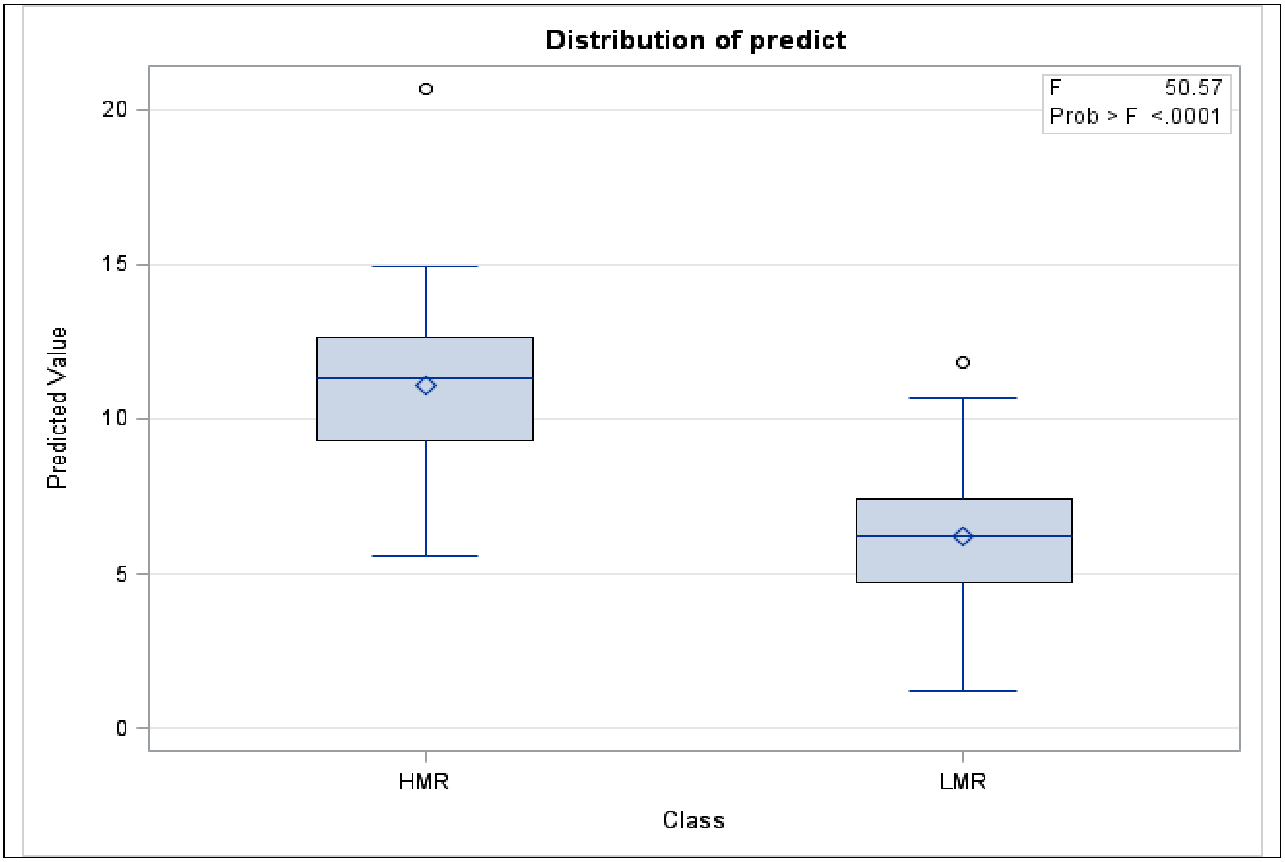

Figure 8 - ANOVA of Predicted Value for LMR and HMR Groups

6.5 Force Versus Displacement Analysis

Researchers theorized that pedal misapplication might be exacerbated by pedals with similar "feel." For example in Figure 8, the force versus deflection response of the brake and accelerator are similar while in Figure 10, the forces versus deflection responses are more distinct.

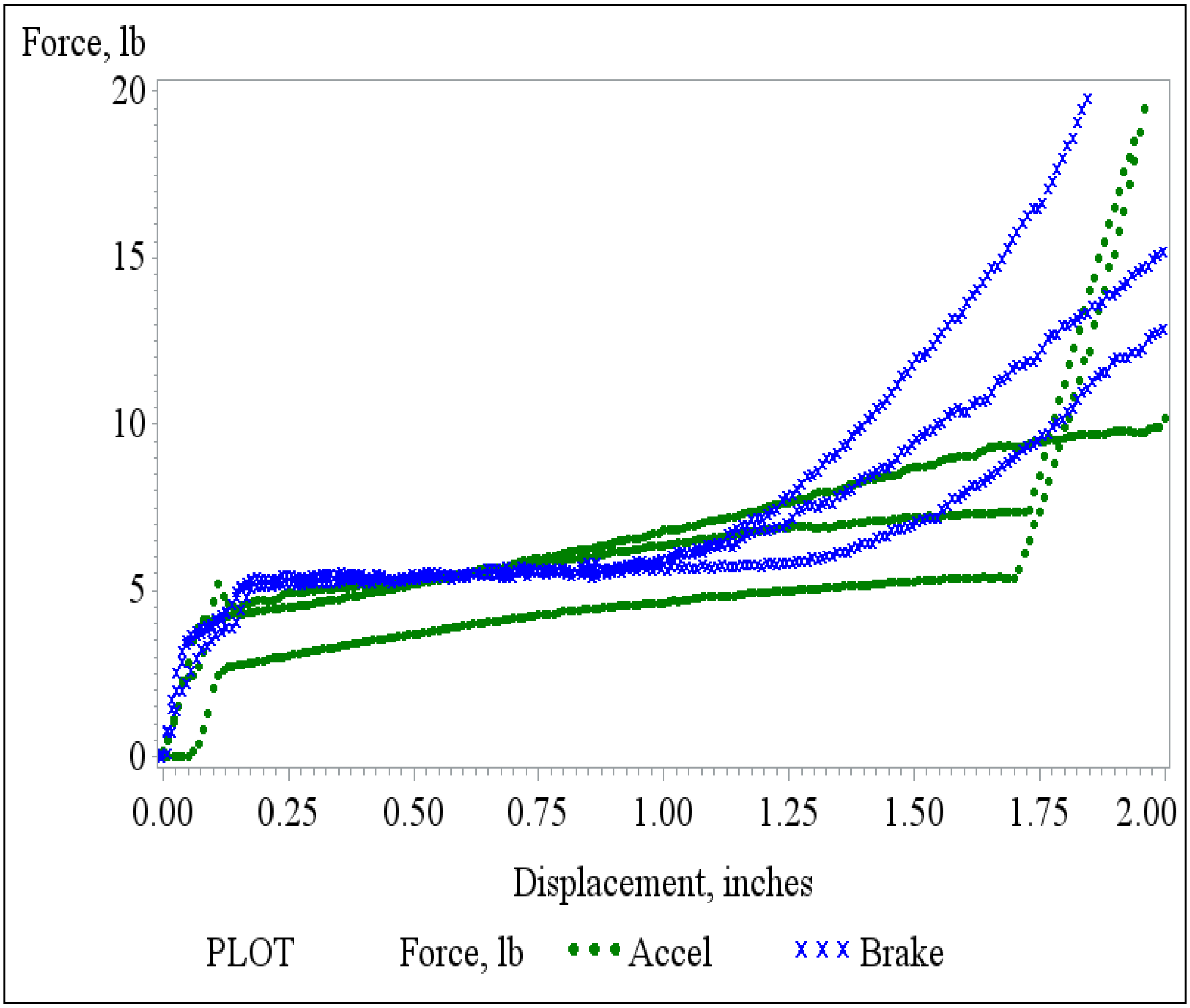

Figure 9. Force Versus Deflection Example for Vehicle With Similar Brake and Accelerator Responses

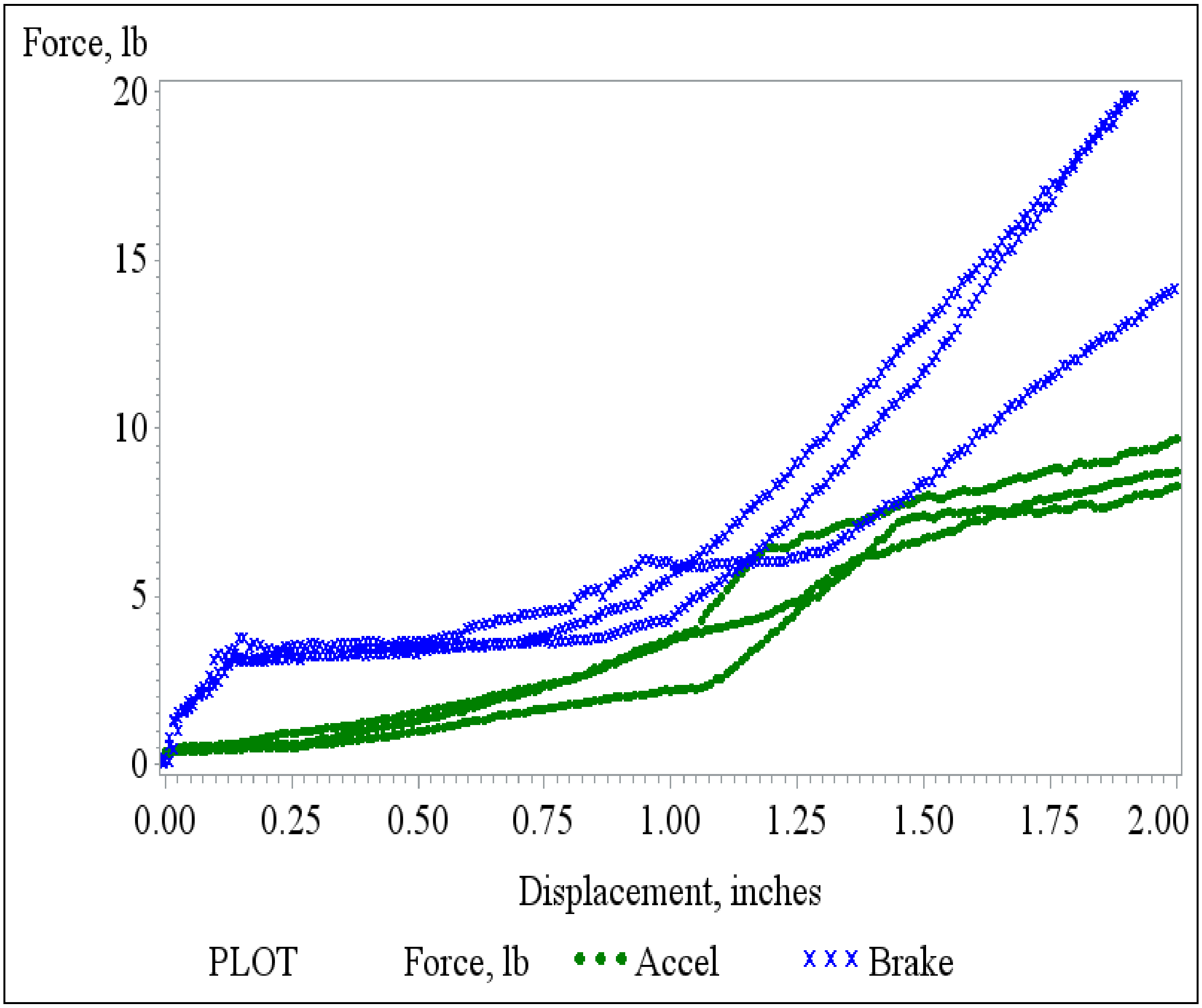

Figure 10. Force Versus Deflection Example for Vehicle With Different Brake and Accelerator Responses

To test the theory, accurate force versus pedal deflection curves were developed for each vehicle. To quantify systematic differences between the LMR and HMR groups, a one-way ANOVA was conducted on each of the following:

- The force at each 0.1 inch of pedal displacement
- The displacement needed to achieve each 1 pound of force
- The force at each 0.1 inch of displacement after 1 pound force was achieved
- The slope of the displacement between 1 pound and 10 pounds of force
- Total displacement between 1 pound and 5 pounds of force
- Total displacement between 1 pound and maximum (~20 pounds) of force
- Total displacement between 5 pounds and 20 pounds of force

- Displacement during plateau force between first negative inflection (~2.5 pounds) and second positive inflection (~10 pounds)

There were no significant differences between the LMR and HMR groups for any of the variables at α=0.05. The 95 percent confidence levels of the difference between the brake and accelerator force at each 0.1 inch deflection for the HMR and LMR groups are shown in Figure 11 below. A complete set of Force Versus Displacement curves for each fundamental vehicle group is available in Appendix E. In summary, the data did not support the theory that pedal misapplication might be exacerbated by pedals with similar "feel."

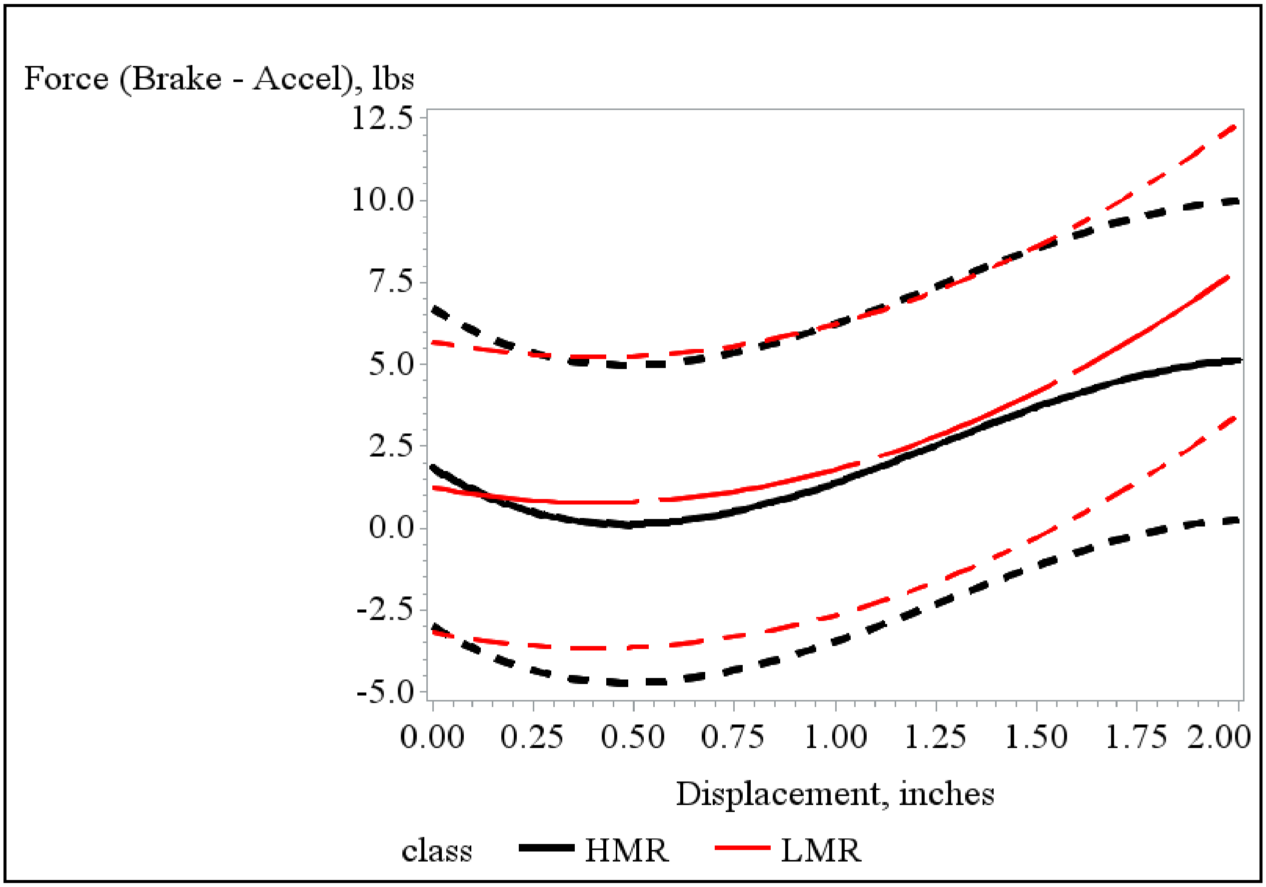

Figure 11 - 95 Percent Confidence Levels for Difference Between Brake-Force and Accelerator-Force Versus Deflection for LMR and HMR Groups, With 95 Percent Confidence Intervals

6.6 Analysis Including Driver Characteristics

Work described thus far focused exclusively on measurements of vehicle dimensions and their correlation to pedal misapplication. Previous investigation of the North Carolina data by NHTSA showed correlation between pedal misapplication rate and driver characteristics such as age, gender, and height.[10] This earlier work hypothesized that driver-vehicle interactions may be important factors. For example, "driver fit" might be related to the height of the driver and position of the vehicle controls, while "driver range of motion" may be related to pedal placement. This theory is consistent with the large number of correlating factors found in this study related to driver alignment. See for example Table 9 and Table 10.

During the analysis of this data, it was discovered that roughly half of the pedal misapplication events studied occurred while drivers were either turning the vehicle or reversing; actions that are generally associated with adjustments to drivers' positions, suggesting that variations in driver positioning may influence pedal misapplication rates. The model also indicated that a narrower seat width was associated with lower rates of pedal misapplication when pedal spacing was large.

For the second analysis, the average age, height, and gender (percent of drivers who were male) of the drivers for the LRM and HRM vehicles in the database were added to the study. Gender and height were found to be highly correlated, and height was retained as the analysis variable since it is a continuous variable. Initially, age and height were added as variables to the best-fit regression model found for pedal dimensions. This showed a modest increase in the R^2 value from 0.48 to 0.57. A stepwise regression was completed including age, height, the interactions of age and height with measured dimensions, and the ratios of age and height to the measured dimensions. The results are shown in Table 16. The predicted versus the measured rate is shown in Figure 12. The high degree of correlation indicates that these variables are likely to be significant for pedal misapplication events. However, the large number of variables included in the study precludes assuming that this is a true predictive model for vehicle rate.

[10] Lococo, Staplin, Martell, & Sifrit, 2012.

Term	Variable 1	Variable 2	Partial R-Square	Model R-Square	F Value	Pr > F
Interaction	Age	Stepover – brake to accel – shortest arc	0.4251	0.4251	69.88	<.0001
Interaction	Height	Right edge of brake to left edge of accel	0.3891	0.8142	57.33	<.0001
Interaction	Age	Right edge of brake to tunnel	0.0385	0.8527	7.58	0.0072
Interaction	Height	Height of steering wheel from floor	0.0265	0.8792	5.48	0.0216
Ratio	Stepover – brake to accel – shortest arc	Brake pedal width	0.027	0.9062	5.9	0.0173
Ratio	Accelerator to tunnel	Bottom edge of brake to undepressed floor	0.0182	0.9244	4.11	0.0457
Ratio	Accelerator to tunnel	Seat cushion width	0.0172	0.9416	4.02	0.0483

Table 16 - Stepwise Regression Model Including Driver Characteristics and Measured Vehicle Dimensions

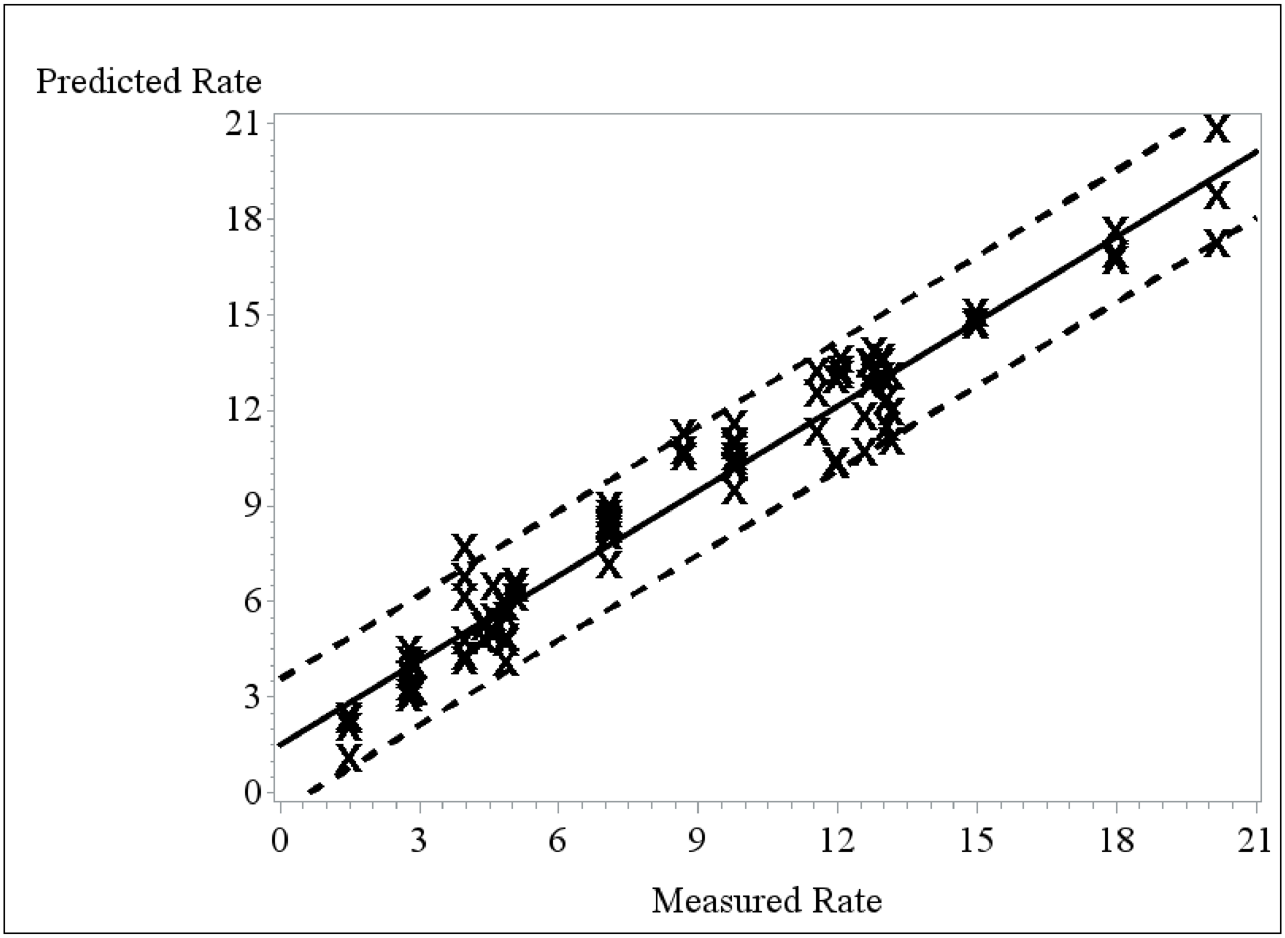

Figure 12 - Predicted Rate of Pedal Misapplication versus the Measured Rate, With 95 Percent Confidence Levels Shown

The two most significant interaction terms are the interaction between the average driver age and the stepover height, and the interaction between the driver height and the separation between the brake and accelerator pedal.

Figure 13 shows the predicted values from the stepwise regression model versus driver age and stepover. The predicted rate increases significantly when stepover is high for older drivers.

In the first analysis, stepover ranked among the most correlated variables, though with a generally negative correlation. Once the driver characteristic of age is added, the correlation is shown to be positive for older drivers, though this does not suggest that low stepover is not a problem for drivers in general. Both effects are significant, with the highest predicted values of pedal misapplication for the greatest age and the largest stepover dimension for older drivers. The effects of driver height and pedal separation predicted from the model for driver heights greater than and less than 66 inches tall are shown in Figure 14. There is generally a higher rate for large pedal separation and taller drivers, whereas the rate is essentially constant for large pedal separation and shorter drivers. Figure 14 also contains 95% confidence bands (dashed lines) that quickly diverge, indicating the model would not make accurate rate predictions for small and excessively large separations.

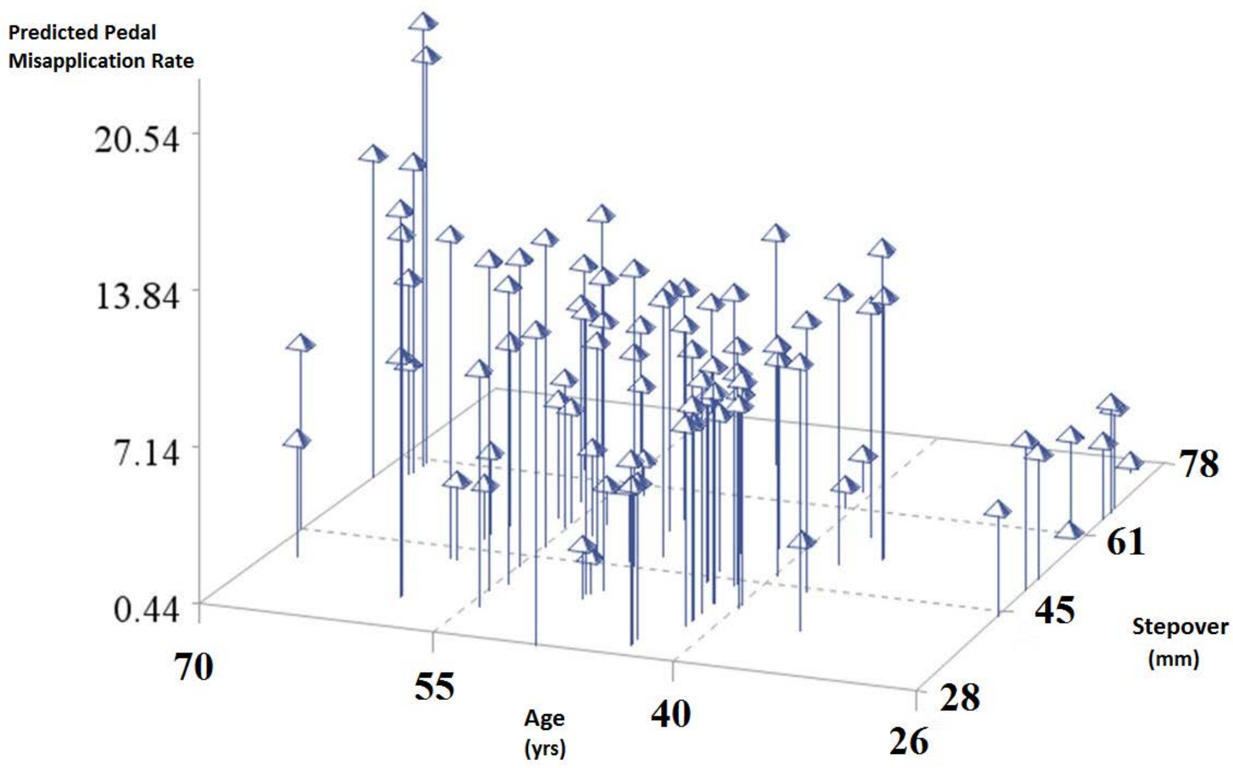

Figure 13 – Effects of the Interaction of Driver Age and Stepover. Predicted Rate Increases Significantly When Stepover is Very High for Older Drivers. Calculated From Stepwise Regression Model With Driver Characteristics and Measured Pedal Dimensions

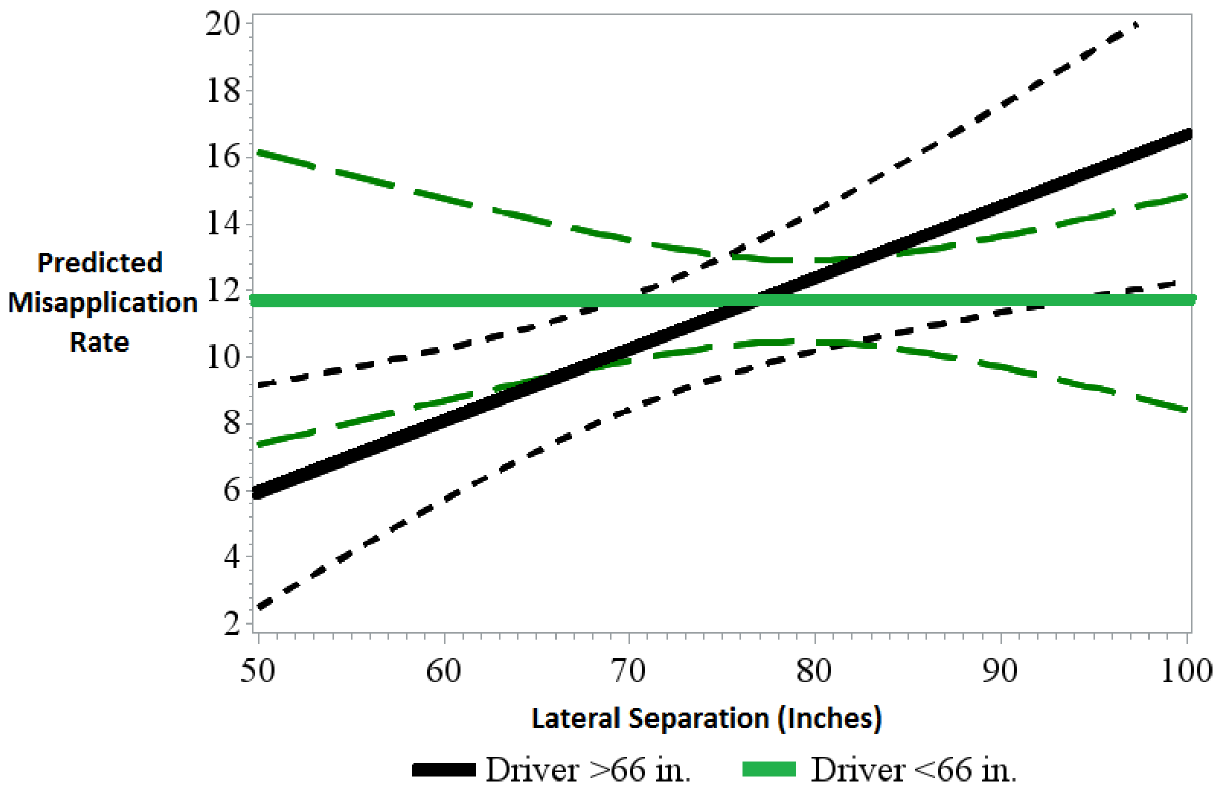

Figure 14 – Effects of the Interaction of Driver Height and Pedal Lateral Separation Shown with 95% Confidence Levels (Dashed Lines). Large Pedal Separation is Predicted to be Associated with Higher Rates of Pedal Misapplication for Taller Drivers Within a Narrow Working Range. Calculated From Stepwise Regression Model With Driver Characteristics and Measured Pedal Dimensions

7.0 SUMMARY AND OBSERVATIONS

NHTSA conducted an exploratory, quantifiable study of the relative locations of pedals in a limited set of passenger cars to determine whether elements of vehicle pedal design and location contribute to the propensity for pedal misapplication. Vehicles from populations of low and high rates of pedal misapplication, taken from the North Carolina State Crash Database, were selected and dimensional variables as defined by an industry standard were measured. A NHTSA software program was used to define vehicle groups that were substantially similar based on factors such as brand, model, and vehicle wheelbase.

Three vehicles of each model were located and measured. The forces and displacements required to operate the accelerator and the brake pedal for each vehicle were also measured but did not prove to be a significant factor in these pedal misapplications.

Statistical correlation between the measured variables and the rate of pedal misapplication in the database was conducted. Stepover and accelerator position were the most correlated pedal dimensions, but no single variable had a high correlation to the misapplication rate. Similarly, no single product or ratio of measured variables had a strong correlation to the misapplication rate.

Standard stepwise regression procedures were carried out to determine if there might be measurements that, when taken in combination, produced a high correlation to pedal misapplication. While this model did not have a high R^2 value (0.476), the predicted rate from the regression versus the measured rate for each individual vehicle indicated that there was a general agreement. In the vehicle dimension-only model, the most correlated pedal dimensions to the misapplication rate were the stepover distance and the distance from the left edge of the brake to the vertical panel on the left. More notably, the most significant variables, when taken together, comprised different populations for the LMR and HMR vehicles.

Previous work showed that driver characteristics such as age, gender, and height were correlated to the pedal misapplication rate in the North Carolina data. A second analysis was conducted to add the average age and height of drivers in the North Carolina data for each vehicle model. When the interactions of age and height with measured data were analyzed, a regression model with good agreement ($R^2 = 0.94$) between predicted and actual rates was found. The two most predictive terms were the interaction between the average driver age and the stepover height, and the interaction between the driver height and the separation between the brake and accelerator pedal. While the introduction of age caused the overall inversion of the correlation of stepover to a positive, it seemed to indicate that high stepover may be related to pedal misapplication for older people, but this does not suggest that low stepover is not a problem for drivers in general.

In summary, both the position of the vehicle controls and their estimated position relative to the seat position show some correlation with the pedal misapplication rate for vehicles in the data set. When taken in conjunction with average driver characteristics, these interactions are more strongly correlated to pedal misapplication. This suggests that optimal pedal dimensions for one demographic may not be optimal for another. While the analyses of this study have provided insights, pedal misapplication continues to be a difficult problem with no apparent optimization, and other data sets such as the North Carolina database do not exist to allow further assessment.

Appendix A

LMR

YEAR	MAKE	MODEL	VIN
1997-2008 Pontiac Grand Prix			
1999	Pontiac	Grand Prix	1G2WP12K9XFXXXXXX
1999	Pontiac	Grand Prix	1G2WP52K5XFXXXXXX
2004	Pontiac	Grand Prix	2G2WR524041XXXXXX
2008	Pontiac	Grand Prix	2G2WP552781XXXXXX
2002-2008 Nissan Altima			
2003	Nissan	Altima	1N4AL11D43CXXXXXX
2007	Nissan	Altima	1N4BL21E77CXXXXXX
2007	Nissan	Altima	1N4AL21E67CXXXXXX
1994-2004 Ford Mustang			
1998	Ford	Mustang	1FAFP42X3WFXXXXXX
2002	Ford	Mustang	1FAFP40412FXXXXXX
2004	Ford	Mustang	1FAFP44684FXXXXXX
1983-1991 Toyota Camry			
1987	Toyota	Camry	JT2SV21E3H3XXXXXX
1990	Toyota	Camry	JT2VV22W2L0XXXXXX
1991	Toyota	Camry	JT2SV21E7M3XXXXXX
1984-1999 Oldsmobile Delta88			
1991	Olds	Delta 88	1G3HN54C1MHXXXXXX
1993	Olds	88 Royale	1G3HN53L5P1XXXXXX
1999	Olds	88	1G3HC52K5X4XXXXXX
1991-2002 Saturn SL			
2001	Saturn	SL1	1G8ZH52891ZXXXXXX
2002	Saturn	SL	1G8ZK52782ZXXXXXX
2002	Saturn	SL1	1G8ZH52832ZXXXXXX
1979-1993 Ford Mustang			
1988	Ford	Mustang	1FABP45E1JFXXXXXX
1991	Ford	Mustang	1FACP42E4MFXXXXXX
1993	Ford	Mustang	1FACP42EBPFXXXXXX
1994-1999 Cadillac DeVille			
1995	Cadillac	Deville	1G6KD52B6SUXXXXXX
1998	Cadillac	Deville	1G6KD54Y9WUXXXXXX
1999	Cadillac	Deville	1G6KD54Y3XUXXXXXX
1982-2002 Chevrolet Camaro			
1987	Chevrolet	Camaro	1G1FP21S3HNXXXXXX
1989	Chevrolet	Camaro	1G1FP21E8KLXXXXXX
1989	Chevrolet	Camaro	1G1FP21EXKLXXXXXX
1994	Chevrolet	Camaro	2G1FP32P3R2XXXXXX
2000	Chevrolet	Camaro	2G1FP22G9Y2XXXXXX
2002	Chevrolet	Camaro	2G1FP22G222XXXXXX
1997-2008 Chevrolet Impala/Caprice			
2003	Chevrolet	Impala	2G1WF52E539XXXXXX
2005	Chevrolet	Impala	2G1WF52E359XXXXXX
2007	Chevrolet	Impala	2G1WT58K379XXXXXX

HMR			
YEAR	MAKE	MODEL	VIN
1992-2008 Mercury Grand Maquis			
1995	Mercury	Grand Marquis	2MELM74W3SXXXXXXX
2006	Mercury	Grand Maquis	2MEFM75W86XXXXXXX
2008	Mercury	Grand Marquis	2MEFM75V58XXXXXXX
2002-2006 Toyota Camry			
2003	Toyota	Camry	4T1BE30KX3UXXXXXX
2004	Toyota	Camry	4T1BE32K14UXXXXXX
2005	Toyota	Camry	4T1BE32K35UXXXXXX
1994-2005 Mitsubishi Galant			
2000	Mitsubishi	Galant	4A3AA46G9YEXXXXXX
2003	Mitsubishi	Galant	4A3AA46H33EXXXXXX
2005	Mitsubishi	Galant	4A3AB36F45EXXXXXX
1993-2001 Toyota Corolla			
2000	Toyota	Corolla	2T1BR12E9YCXXXXXX
2000	Toyota	Corolla	2T1BR12E1YCXXXXXX
2001	Toyota	Corolla	1NXBR12E91ZXXXXXX
2003-2008 Toyota Corolla			
2003	Toyota	Corolla	1NXBR32E53ZXXXXXX
2007	Toyota	Corolla	2T1BR32E07CXXXXXX
2007	Toyota	Corolla	2T1BR32E17CXXXXXX
1993-2001 Nissan Altima			
1994	Nissan	Altima	1N4BU31D0RCXXXXXX
2001	Nissan	Altima	1N4DL01D31CXXXXXX
2001	Nissan	Altima	1N4DL01D21CXXXXXX
1995-2006 Dodge Stratus			
1999	Dodge	Stratus	1B3EJ46X9XNXXXXXX
2004	Dodge	Stratus	4B3AG42G44EXXXXXX
2006	Dodge	Stratus	1B3EL46X06NXXXXXX
1986-1995 Ford Taurus			
1994	Ford	Taurus	1FALP52U5RAXXXXXX
1995	Ford	Taurus	1FALP52U5SAXXXXXX
1995	Ford	Taurus	1FALP52U4SAXXXXXX
1995-2006 Nissan Sentra			
2002	Nissan	Sentra	3N1CB51D32LXXXXXX
2004	Nissan	Sentra	3N1CB51D04LXXXXXX
2006	Nissan	Sentra	3N1CB51D16LXXXXXX
1995-2004 Toyota Avalon			
1995	Toyota	Avalon	4T1GB11E5SUXXXXXX
1997	Toyoya	Avalon	4T1BF12B8VUXXXXXX
2000	Toyota	Avalon	4T1BF28B6YUXXXXXX

Special Interest

YEAR	MAKE	MODEL	VIN
1994 Honda Accord			
1994	Honda	Accord	JHMCD5633RCXXXXXX
1994	Honda	Accord	1HGCD5658RAXXXXXX
1994	Honda	Accord	1HGCD5668RAXXXXXX
1999 Honda Accord			
1999	Honda	Accord	1HGCG6650XAXXXXXX
1999	Honda	Accord	1HGCG564XXAXXXXXX
1999	Honda	Accord	1HGCG3259XAXXXXXX
2003 Honda Accord			
2003	Honda	Accord	1HGCM56613AXXXXXX
2003	Honda	Accord	1HGCM82603AXXXXXX
2003	Honda	Accord	1HGCM72673AXXXXXX
2003	Honda	Accord	1HGCM82673AXXXXXX
1992 Honda Civic			
1992	Honda	Civic	1HGEG8649NLXXXXXX
1992	Honda	Civic	1HGEG8657NLXXXXXX
1992	Honda	Civic	1HGEG8651NLXXXXXX
1997 Honda Civic			
1997	Honda	Civic	2HGEJ6673VHXXXXXX
1997	Honda	Civic	1HGEJ6225VLXXXXXX
1997	Honda	Civic	1HGEJ8677VLXXXXXX
2005 Honda Civic			
2005	Honda	Civic	1HGEM22185LXXXXXX
2005	Honda	Civic	2HGES26855HXXXXXX
2005	Honda	Civic	1HGEM22905LXXXXXX
1992-2008 Ford Crown Victoria			
1999	Ford	Crown Victoria	2FAFP71W93XXXXXXX
2003	Ford	Crown Victoria	2FAHP71W83XXXXXXX
2005	Ford	Crown Victoria	2FAFP73W95XXXXXXX
1985 Audi 5000			
1985	Audi	5000	WAUHC0449FNXXXXXX
1985	Audi	5000	WAUGB0444FA1XXXXXX
1987	Audi	5000	WAUFC0442HNXXXXXX
2005 Cadillac STS			
2005	Cadillac	STS	1G6DW677450XXXXXX
2005	Cadillac	STS	1G6DC67A350XXXXXX
2005	Cadillac	STS	1G6DC67A450XXXXXX
2008 Cadilac STS			
2008	Cadillac	STS	1G6DD67V180XXXXXX
2008	Cadillac	STS	1G6DW67V680XXXXXX
2008	Cadillac	STS	1G6DL67A98015XXXXXX
2005 Cadillac CTS			
2005	Cadillac	CTS	1G6DP567450XXXXXX
2005	Cadillac	CTS	1G6DP567150XXXXXX
2005	Cadillac	CTS	1G6DP567850XXXXXX
1985-1991 Buick LeSabre			
1985	Buick	LeSabre	1G4BP37Y7FHXXXXXX
1990	Buick	LeSabre Limited	1G4HR54CXLHXXXXXX
1991	Buick	LeSabre Custom	1G4HP54C5MHXXXXXX

Appendix B

Pedal Force Electronics Equipment List

Signal Conditioning Component	Model	Manufacture
16-Channel Backplane	3B01	Analog Devices, Inc.
Amplifier	3B18	Analog Devices, Inc.
DC-Power Supply	KW40-12-15T797	Polytron Devices, Inc.

Data Acquisition Components	Model	Manufacture
Touch Pad Computer	XRT	Walk About Computers, Inc.
Analog to Digital Acquisition Board	DAS16/16	Measurement Computing, Inc.

Stepper Motor Control Components	Model	Manufacture
Stepper Motor	LA23ECKC13	Eastern Air Devices, Inc.
Stepper Motor Controller	IM4831	Intelligent Motion Systems, Inc.
Touch Pad Computer	XRT	Walk About Computers, Inc.

Instrumentation Hardware	Model	Manufacture
Load Cell	LC703-50	Omegadyne, Inc.
Linear Potentiometer	CLP150	Celesco

3D Scanning Electronics Equipment List

Data Acquisition Components	Model	Manufacture
Laptop Computer	M6600	Dell, Inc.
3D Laser Scanner	EXAscan	Creaform, Inc.

Appendix C

List of test vehicles measurements

Vehicle	"A" PV-17	"B" PV-21	"C" PV-27	"D" PV-42	"E" PV-82	"F" PV-92	"G" PV-98	"H" PL-52	"I" PH-26	"J" PH-16	"L" SV-16	"M" No ID	"N" PL-1	"O" PV-47	"P" H-17	"Q" V-9	"R" L-6	"S" PV-22	"T" PV-11	Pedal Arc Radius	Pedal Arc Chord
1995 Mercury Grand Marquis	51.3	74.0	193.8	221.1	156.7	33.1	125.4	58.0	181.3	95.6	600.0	48.1	50.7	561.5	614.8	379.6	610.8	125.2	42.6	216.4	53.4
2008 Mercury Grand Marquis	66.1	68.4	192.3	239.6	140.4	11.3	92.4	60.3	154.7	89.9	651.3	53.3	61.2	572.8	588.3	378.9	604.9	114.3	45.6	227.5	68.3
2006 Mercury Grand Marquis	60.5	57.5	175.5	241.4	134.4	45.1	32.0	59.8	153.7	97.0	649.7	36.7	64.4	581.6	614.0	378.9	588.4	116.3	49.8	296.7	70.0
2005 Ford Crown Victoria	55.7	61.2	179.4	239.3	144.2	0.8	81.9	49.7	171.7	96.3	668.2	49.3	54.1	573.0	603.6	379.8	593.9	125.1	48.4	62.0	66.0
2003 Ford Crown Victoria	47.6	71.0	188.5	230.6	144.0	3.3	77.4	62.9	165.1	87.9	550.2	44.7	62.1	560.5	609.4	383.0	597.6	126.3	49.0	66.1	47.3
2003 Ford Crown Victoria	60.4	75.8	200.4	224.8	152.9	14.5	104.7	66.0	176.2	101.9	545.1	44.8	56.2	563.3	619.4	383.9	585.1	124.0	50.3	163.9	52.2
2004 Toyota Camry	47.4	88.7	179.9	248.8	154.7	51.5	148.9	33.8	151.3	128.4	521.3	4.3	45.7	523.9	650.1	380.4	539.8	117.3	43.7	344.3	73.9
2005 Toyota Camry	48.8	81.4	176.8	246.9	151.8	78.4	168.5	42.0	154.0	127.5	517.0	2.3	37.4	523.8	664.5	381.1	534.7	119.7	45.7	190.7	71.1
2003 Toyota Camry	49.0	84.5	178.2	246.1	156.1	69.7	168.4	34.0	140.8	120.2	522.9	16.8	32.8	519.8	677.8	381.6	509.6	117.1	42.2	259.5	77.1
2000 Mitsubishi Galant	41.8	83.1	153.8	246.3	154.7	39.0	138.1	39.7	156.1	110.9	499.1	37.8	31.4	515.7	669.5	386.8	505.0	109.5	38.8	199.8	67.6
2005 Mitsubishi Galant	33.9	87.3	159.3	194.1	174.8	71.1	175.4	39.1	155.4	125.1	515.0	2.0	34.2	489.5	606.9	382.1	567.6	138.0	41.3	197.3	77.7
2003 Mitsubishi Galant	44.1	86.1	170.9	253.4	157.0	38.3	140.0	46.1	150.9	100.6	497.4	38.1	45.1	531.7	663.4	386.1	491.5	109.4	39.3	227.0	65.3
2000 Toyota Corolla	37.1	84.8	157.2	215.9	153.1	81.9	181.8	44.8	154.5	101.6	535.6	5.8	39.8	478.2	630.7	376.7	522.4	103.8	41.6	117.6	76.4
2000 Toyota Corolla	36.4	87.8	159.6	210.4	156.3	65.4	168.6	28.0	153.1	110.6	517.4	2.0	17.4	473.7	635.0	385.6	523.8	107.2	41.2	166.8	77.1
2001 Toyota Corolla	27.5	97.1	163.6	211.7	167.3	68.7	180.9	39.5	151.1	106.0	523.2	4.8	35.1	478.5	628.1	369.3	525.2	103.9	43.5	146.1	74.4
2006 Nissan Sentra	49.5	67.6	166.7	228.6	148.7	52.7	139.1	55.8	154.6	126.3	524.0	11.2	65.2	516.1	598.7	380.8	573.2	128.6	48.0	369.7	58.6
2002 Nissan Sentra	24.8	72.2	170.5	225.7	149.5	48.6	134.4	43.8	166.0	146.7	509.0	4.8	51.0	521.1	596.5	381.6	574.5	129.0	45.0	260.7	70.7
2004 Nissan Sentra	44.0	77.7	172.6	226.6	153.4	56.4	145.4	49.8	144.0	115.9	527.4	9.1	57.3	540.0	607.5	381.2	546.3	131.3	44.2	129.4	66.9
2006 Dodge Stratus	67.4	52.4	176.7	240.0	161.5	81.0	171.1	55.1	150.9	101.7	511.3	2.5	63.6	565.7	624.6	384.3	584.8	137.4	45.5	105.3	46.5
1999 Dodge Stratus	78.9	52.5	189.8	238.9	164.8	50.2	146.1	52.4	151.3	115.3	521.7	10.5	45.5	573.8	638.9	382.4	571.5	135.5	44.6	201.6	49.6
2004 Dodge Stratus	60.1	81.3	189.7	256.8	157.9	19.1	123.5	38.5	171.2	130.9	521.8	42.3	39.6	567.1	616.0	380.4	554.3	108.9	43.3	156.6	70.4
1995 Ford Taurus	32.3	77.3	176.2	231.1	166.3	96.4	199.8	47.4	151.5	110.7	525.1	13.7	56.9	552.5	646.9	383.8	584.6	123.8	64.1	176.9	58.4
1995 Ford Taurus	28.6	63.6	163.1	268.6	163.0	87.6	190.4	68.1	159.1	113.6	615.9	26.8	79.6	587.1	657.6	386.0	585.7	122.8	69.5	255.6	56.1
1994 Ford Taurus	44.6	64.6	189.1	229.7	164.0	72.8	175.9	51.4	154.4	102.8	608.4	13.9	66.0	574.8	688.8	383.4	551.8	123.8	68.7	176.8	64.2
1997 Toyota Avalon	15.7	79.9	129.7	219.3	160.0	103.8	199.3	55.3	158.9	120.1	520.5	1.2	50.5	467.5	656.0	380.0	555.7	123.5	43.0	161.1	70.8
1995 Toyota Avalon	21.1	82.9	141.2	217.2	159.8	65.5	163.0	33.7	166.1	135.7	612.1	3.5	39.7	473.9	631.7	379.1	576.6	123.5	43.4	141.5	79.3
2000 Toyota Avalon	42.6	90.7	169.6	220.0	156.8	80.5	178.1	38.6	156.2	128.8	525.3	14.1	35.5	485.9	658.0	380.8	529.9	117.6	39.6	351.7	92.3
1990 Buick Lesabre Limited	72.1	63.6	188.9	257.9	158.9	46.8	137.0	56.2	162.9	123.3	538.3	17.8	55.6	606.3	626.0	375.2	589.3	136.2	52.2	191.7	50.3
1991 Buick LeSabre	66.5	60.9	186.4	269.6	151.0	89.3	169.1	62.3	174.3	129.0	537.1	17.7	62.5	616.5	616.2	373.8	600.0	136.6	54.4	59.9	47.9
1985 Buick LeSabre	11.7	74.0	196.7	224.4	164.0	7.9	84.7	65.1	163.1	11.8	545.5	62.6	73.8	589.5	670.0	374.0	540.4	146.3	73.8	-	-
1987 Buick LeSabre	83.8	54.7	194.6	283.8	147.0	86.1	167.0	44.2	161.0	123.6	549.5	34.9	49.8	627.9	616.8	375.2	575.6	134.3	55.4	214.0	71.4
2003 Chevy Impala	29.9	70.4	179.3	229.0	176.0	87.5	194.1	39.1	173.7	126.0	599.2	18.4	46.1	561.7	670.2	399.9	557.4	132.3	75.3	171.7	63.0
2007 Chevrolet Impala	36.0	65.1	187.9	231.2	164.0	92.7	190.9	57.7	170.9	106.9	534.5	33.3	65.5	551.4	675.2	392.4	552.4	134.2	72.0	222.6	70.7
2005 Chevrolet Impala	30.5	70.5	190.0	271.3	181.8	81.3	189.2	56.3	166.6	108.3	546.1	12.4	52.5	586.5	664.5	387.1	541.4	134.1	72.6	74.6	45.7
1999 Pontiac Grand Prix	30.4	68.1	166.5	258.2	155.9	85.2	174.2	64.5	169.1	116.2	525.9	32.8	77.8	551.1	676.8	387.4	562.5	138.8	56.3	133.7	48.7
2004 Pontiac Grand Prix	50.7	52.6	172.7	276.5	146.3	126.0	202.9	52.7	169.3	112.3	516.7	46.1	68.9	571.1	673.7	392.9	549.9	136.7	54.1	153.9	61.5
1999 Pontiac Grand Prix	34.1	70.0	174.5	266.2	161.4	84.6	175.3	61.0	175.0	119.2	538.8	27.5	69.4	572.9	668.6	387.0	554.3	136.5	57.0	144.3	64.4
2008 Pontiac Grand Prix	45.1	63.4	180.1	272.2	150.6	94.9	178.8	52.8	176.8	113.5	511.3	33.3	65.5	580.0	689.2	396.2	556.9	135.5	53.1	49.9	33.4
1991 Olds 88	75.9	68.5	189.6	270.9	153.7	86.9	170.9	56.2	157.5	118.4	552.4	25.5	63.0	623.3	639.7	375.7	569.0	135.4	53.9	153.2	66.8
1999 Oldsmobile 88	77.6	54.6	188.7	265.3	149.8	106.7	189.3	52.3	160.4	128.1	573.5	17.1	50.2	595.1	629.8	393.6	578.4	134.6	53.6	207.7	51.6
1993 Oldsmobile 88 Royale	58.5	49.6	184.3	263.6	150.6	97.7	178.7	67.1	167.7	109.6	538.8	0.7	68.0	592.1	668.0	391.9	562.7	136.7	56.1	122.2	45.6
1990 Toyota Camry	47.8	93.2	179.1	214.7	167.3	60.4	167.4	37.4	115.4	108.5	509.9	16.5	34.4	537.2	616.2	390.1	517.5	124.2	43.3	201.8	70.8
1991 Toyota Camry	59.8	89.0	185.5	228.4	167.1	77.3	182.1	38.7	122.1	108.3	545.6	1.8	35.8	535.9	583.9	390.0	533.2	124.4	41.6	438.0	76.7
1987 Toyota Camry	62.9	90.9	185.3	216.0	165.9	79.0	181.2	45.5	103.8	89.4	532.7	18.2	43.1	556.7	579.6	390.0	528.2	123.8	43.9	323.1	73.4
1998 Cadillac DeVille	41.1	66.6	174.0	227.8	175.0	103.2	205.5	51.8	142.4	103.7	559.9	32.0	56.7	532.8	642.0	392.1	576.7	139.3	56.8	92.8	52.9
1999 Cadillac DeVille	40.0	78.4	174.1	241.1	172.0	92.6	194.7	50.7	149.1	107.5	530.8	29.6	56.4	544.1	628.4	392.0	588.8	137.3	50.3	184.8	52.4
1995 Cadillac DeVille	46.2	56.0	169.9	261.8	160.2	96.9	188.3	77.6	156.6	98.7	596.9	25.5	74.1	555.4	624.3	393.0	606.6	138.1	53.3	266.2	38.1
1988 Ford Mustang	51.1	60.8	149.1	206.9	121.2	25.9	103.5	61.4	138.0	104.8	544.6	66.8	69.3	451.2	605.4	367.5	581.3	81.8	29.2	138.9	58.5
1993 Ford Mustang	38.4	81.0	144.9	237.3	122.3	14.8	94.4	62.8	143.1	111.4	498.5	49.3	66.0	455.0	594.4	385.1	623.2	83.4	28.2	779.5*	61.1
1991 Ford Mustang	41.4	79.6	158.0	231.0	130.1	19.3	109.6	72.2	159.2	119.1	524.0	55.4	71.0	470.9	581.3	384.7	645.6	82.0	27.2	108.3*	61.8
2001 Saturn SL1	43.8	65.3	161.2	282.4	139.9	88.2	172.9	47.6	139.1	99.8	520.2	53.1	50.4	549.7	607.1	370.7	577.6	106.9	43.4	222.4	52.4
2002 Saturn SL	42.8	66.0	161.2	285.2	141.0	89.7	175.8	42.0	130.9	88.6	519.6	29.4	48.4	548.1	607.1	369.2	565.5	105.8	43.4	163.7	64.1
2002 Saturn SL1	35.3	63.3	151.8	292.2	135.3	84.3	166.6	46.7	139.2	96.0	523.4	47.4	52.4	542.6	612.6	371.2	573.4	105.9	45.5	153.1	50.9
2007 Nissan Altima	25.8	83.4	153.8	313.2	136.3	82.2	169.5	52.3	141.2	127.9	526.7	48.0	54.4	552.8	638.3	380.3	581.1	101.8	45.5	148.8	56.3
2007 Nissan Altima	27.6	84.3	153.9	310.3	145.7	75.7	169.1	49.8	139.6	115.7	522.4	33.4	56.2	548.7	667.2	380.0	593.9	103.2	42.7	290.4	57.6
2003 Nissan Altima	32.7	85.2	162.4	270.6	165.4	86.5	187.9	58.9	153.9	122.3	509.0	25.9	58.3	550.9	644.4	391.2	558.6	125.1	45.3	222.8	68.4
1998 Ford Mustang	17.1	82.5	151.6	212.1	143.1	20.5	112.4	62.3	149.9	115.8	529.1	76.3	47.9	461.4	587.7	381.7	637.5	95.2	49.4	282.2	47.6
2002 Ford Mustang	31.0	79.6	156.5	207.8	136.3	8.9	97.4	62.1	148.0	112.6	513.2	74.1	53.6	471.2	606.4	381.8	613.3	97.8	43.4	240.0	49.6
2004 Ford Mustang	19.0	96.4	162.5	215.6	140.4	1.3	97.4	74.7	151.9	110.6	490.9	73.7	68.8	461.4	601.0	381.3	635.7	88.8	45.3	234.5	49.8

List of test vehicles measurements

Vehicle	"A" PV-17	"B" PV-21	"C" PV-27	"D" PV-42	"E" PV-82	"F" PV-92	"G" PV-98	"H" PL-52	"I" PH-26	"J" PH-16	"L" SV-16	"M" No ID	"N" PL-1	"O" PV-47	"P" H-17	"Q" V-9	"R" L-6	"S" PV-22	"T" PV-11	Pedal Arc Radius	Pedal Arc Chord
1989 Chevrolet Camaro	21.4	68.8	139.6	228.7	151.3	42.4	119.1	64.7	129.8	87.3	487.8	49.4	67.6	529.8	589.4	367.1	583.9	150.0	50.9	337.0	50.6
1987 Chevrolet Camaro RS	15.1	90.3	149.1	213.4	160.6	30.3	115.8	67.0	132.3	76.9	519.4	69.0	67.3	531.1	625.7	368.8	564.1	145.5	49.8	-	-
1989 Chevrolet Camaro	27.0	65.3	145.2	194.6	153.8	52.2	132.7	48.8	143.8	103.4	539.7	40.8	66.0	494.7	624.4	-	604.8	145.3	51.1	18.1	24.1
1994 Chevrolet Camaro	15.5	91.0	155.0	207.9	161.8	28.2	129.6	66.1	140.2	98.1	491.7	48.5	56.0	500.5	590.8	374.5	604.1	116.9	45.9	129.3"	38.7
2002 Chevrolet Camaro	4.5	91.6	136.1	221.2	159.2	31.9	131.1	43.4	136.1	114.7	478.7	44.6	40.8	498.6	561.1	392.2	613.4	119.6	44.5	196.5	43.7
2000 Chevrolet Camaro	7.2	95.3	144.4	214.0	162.7	32.3	135.2	51.5	144.9	114.0	491.2	35.6	51.0	487.8	569.7	392.9	624.2	118.7	45.5	79.1	37.8
1994 Honda Accord	33.7	84.5	156.5	193.0	170.4	52.8	146.6	35.9	158.8	126.4	496.6	20.5	37.4	483.5	620.2	380.1	549.5	148.8	41.8	169.9	65.7
1994 Honda Accord	45.2	82.4	162.3	189.2	171.5	57.0	153.4	43.8	156.1	121.2	481.9	18.6	52.2	492.1	609.2	381.4	555.8	149.4	42.1	201.0	56.4
1994 Honda Accord	45.5	84.4	157.2	188.5	168.5	52.8	148.8	51.3	154.8	120.8	458.3	9.2	53.5	480.0	608.2	378.9	568.5	148.3	35.4	210.4	62.9
1999 Honda Accord	48.8	82.0	171.7	208.0	159.4	60.4	155.6	43.8	157.5	125.3	487.6	11.1	36.1	512.9	615.8	381.2	545.8	128.3	39.1	178.2	61.4
1999 Honda Accord	56.5	84.5	182.5	195.5	165.0	50.1	149.3	35.7	157.2	128.7	466.3	19.6	37.5	504.1	617.6	380.7	540.1	128.0	42.2	254.2	62.6
1999 Honda Accord	44.7	78.5	163.4	207.0	159.7	64.7	156.5	34.7	155.9	128.9	500.6	16.4	32.0	499.3	616.2	380.3	545.0	129.7	38.8	229.8	65.1
2003 Honda Accord	31.8	78.6	165.4	214.5	164.3	66.9	165.7	37.3	147.4	111.7	493.8	5.2	41.1	500.0	626.0	379.6	539.6	129.7	53.4	225.3	67.7
2003 Honda Accord	29.0	79.7	164.9	205.0	166.6	66.6	167.3	39.5	151.0	111.7	503.9	2.5	45.8	493.7	623.5	380.2	541.6	130.3	54.3	203.7	69.0
2003 Honda Accord	27.0	80.5	161.9	219.5	166.8	70.4	169.0	43.2	147.7	111.6	496.7	7.0	42.4	501.6	654.0	380.9	557.9	129.5	53.5	183.0	60.0
1992 Honda Civic	58.1	74.3	171.7	242.7	159.1	73.5	166.7	43.7	162.7	116.8	539.2	21.3	46.5	572.1	628.2	382.1	527.0	127.0	38.8	270.0	68.8
1992 Honda Civic	56.1	77.4	169.9	264.2	159.2	66.2	159.7	45.6	159.5	122.9	540.5	10.9	49.1	600.9	590.8	381.1	568.0	132.2	39.5	266.4	69.6
1992 Honda Civic	54.4	81.1	176.8	259.9	161.1	55.5	149.0	44.9	159.3	123.2	517.2	16.6	52.8	570.3	608.9	381.1	545.7	130.3	39.4	166.8	81.5
1997 Honda Civic	54.6	76.6	179.0	209.6	158.0	58.4	152.0	43.2	175.1	125.0	491.8	18.2	42.1	529.3	616.7	382.0	558.7	125.0	41.4	272.3	67.5
1997 Honda Civic	46.0	76.8	168.5	205.8	157.7	46.7	142.0	49.6	161.0	120.3	500.8	10.5	50.5	529.0	621.7	381.5	543.4	130.2	40.6	288.6	74.9
1997 Honda Civic	45.1	86.3	176.6	206.0	167.5	76.0	172.5	48.9	167.6	109.7	514.6	25.0	47.3	514.0	635.8	381.9	528.5	130.2	39.0	139.7	63.7
2005 Honda Civic	48.7	79.8	168.6	220.6	159.8	64.2	160.1	31.0	147.8	112.9	502.3	23.6	30.7	520.8	616.8	380.5	542.5	129.9	39.3	185.3	61.3
2005 Honda Civic	46.0	72.9	161.1	231.0	154.2	65.6	154.0	32.2	153.3	129.2	496.6	5.9	31.0	516.5	633.7	380.8	540.4	130.2	39.8	296.2	80.6
2005 Honda Civic	44.6	72.6	156.3	226.7	153.1	123.5	211.1	30.3	140.2	111.0	494.4	24.2	26.8	518.4	636.8	376.0	515.4	129.1	38.9	365.0	63.4
1985 Audi 5000	25.2	77.3	168.5	256.8	134.8	25.8	60.5	70.0	177.2	116.2	549.7	76.6	72.9	516.6	676.5	378.8	535.6	98.7	54.7	145.1	65.3
1985 Audi 5000	42.1	79.7	174.7	261.5	136.7	8.0	82.1	22.0	182.3	167.3	533.6	74.4	25.7	511.3	662.7	387.1	538.7	97.9	50.4	223.0	68.5
1987 Audi 5000	7.6	76.6	141.1	257.0	128.9	26.2	106.7	72.8	188.5	115.7	560.9	65.4	73.0	482.1	657.7	386.3	573.4	98.5	47.2	289.1	58.7
2005 Cadillac STS	31.7	70.1	160.2	234.3	149.3	49.6	148.6	55.4	138.4	109.2	490.8	7.6	53.3	487.1	614.8	389.6	595.7	98.9	50.9	235.4	73.4
2005 Cadillac STS	33.9	75.7	164.0	233.3	149.4	55.6	155.3	53.8	153.8	121.1	505.3	10.9	57.3	485.9	607.2	391.5	606.1	99.1	46.7	249.5	71.6
2005 Cadillac STS	17.8	81.4	144.9	236.1	157.2	50.3	156.3	57.7	140.6	106.2	514.7	9.2	58.1	473.3	589.5	390.5	567.3	100.2	48.5	326.9	68.3
2008 Cadillac STS	31.2	77.9	150.3	225.5	150.9	50.9	151.3	63.4	145.5	110.2	514.5	15.9	64.5	473.4	621.6	380.5	551.9	99.3	48.5	207.4	68.6
2008 Cadillac STS	24.6	77.8	153.8	226.3	155.7	34.9	141.9	48.3	139.2	115.8	501.6	6.2	55.2	468.5	629.3	380.5	549.6	99.1	47.7	430.5	71.0
2008 Cadillac STS	21.7	82.5	146.3	236.0	161.4	55.9	166.1	61.3	154.4	112.1	513.0	30.0	61.9	470.4	609.8	380.4	582.2	99.8	46.7	196.1	70.7
2005 Cadillac CTS	27.2	79.3	160.3	252.8	149.6	48.2	149.2	59.7	162.2	112.5	499.4	5.7	52.8	502.2	650.0	390.0	554.6	98.4	43.2	123.7	63.8
2005 Cadillac CTS	34.3	75.4	158.1	257.2	146.5	66.2	161.5	60.5	154.6	101.7	495.3	4.0	52.3	504.0	665.0	389.4	530.8	100.3	45.4	246.6	66.8
2005 Cadillac CTS	30.9	75.2	159.0	251.3	146.4	56.7	152.5	61.0	164.8	116.8	503.4	4.0	54.5	496.1	609.9	389.8	580.8	100.6	46.3	219.9	64.6
2000 Honda Accord	49.2	79.7	169.6	208.9	154.2	73.3	161.8	39.6	162.8	125.3	495.6	16.1	40.1	499.5	625.4	380.5	544.2	129.3	37.8	190.6	57.5