US Department
of Transportation

**National Highway
Traffic Safety
Administration**

DOT HS 809 875 **June 2005**

An Assessment of Human Driver Steering Capability

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS 809 875		

4. Title and Subtitle
An Assessment of Human Driver Steering Capability

5. Report Date
June 2005

6. Performing Organization Code
NHTSA/NVS-312

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8. Performing Organization Report No.

9. Performing Organization Name and Address
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10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
National Highway Traffic Safety Administration
400 Seventh Street, S.W.
Washington, D.C. 20590

13. Type of Report and Period Covered
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report used double lane change data collected during NHTSA's Light Vehicle Handling and ESC Effectiveness Research Program to document the steering capability of human drivers in a highly transient situation. To achieve the best compromise between high maneuver severity and reasonably low path variability, modified ISO 3888 Part 2 lane change geometry was used.

Three independent variables were considered: steering wheel angle (SWA), steering wheel rate (SWR), and steering wheel torque (SWT). The effect of three factors (driver, vehicle, and whether ESC was enabled or disabled), and one interaction term (vehicle and ESC) on these variables was investigated.

The data presented in this paper clearly indicate drivers are capable of achieving very large handwheel inputs—even for relatively long periods of time. A maximum SWA of 578 degrees, and a maximum peak-to-peak SWA of 1118 degrees, were observed during an ESC enabled test performed with the Toyota 4Runner.

A maximum, instantaneous peak SWR of 1819 deg/sec was recorded during an ESC disabled test performed with the Toyota Camry. Even when filtered with the most aggressive filter used in this study, the data indicate it is possible for the human driver to sustain a SWR of 963 deg/sec for one second, witnessed during a disabled ESC test performed with the Chevrolet Corvette.

A maximum, instantaneous peak SWT of 33.9 lbf-ft (46.0 N-m) was observed during an enabled ESC test performed with the Volvo XC90. The ability of the driver to achieve high SWT was reduced greatly over time. In the extreme case where the driver is attempting to maintain the application of SWT for approximately one second, the largest peak SWT observed was 14.1 lbf-ft (19.1 N-m), 58.4 percent less than the maximum instantaneous peak value produced during the same test (albeit processed with a different filter).

Using the GLM procedure in SAS, the statistical significance of the driver, ESC, vehicle, and the interaction of vehicle and ESC was assessed. These analyses each indicate, to varying degrees, that different vehicles and/or vehicle configurations are capable of imposing different demands on the drivers. The significance of each factor varied, and depends on whether SWA, SWR, or SWT data is being considered.

17. Key Words
Dynamic Testing, Steering Angle, Steering Rate, Steering Torque, Test Maneuvers, Rollover, Handling, ESC

18. Distribution Statement
Document is available to the public from the National Technical Information Service Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

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CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
in	inches	2.54	centimeters	cm
ft	feet	30.48	centimeters	cm
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.45	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
mi^2	square miles	2.59	square kilometers	km^2
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.45	kilograms	kg
		PRESSURE		
psi	pounds per $inch^2$	0.07	bar	bar
psi	pounds per $inch^2$	6.89	kilopascals	kPa
		VELOCITY		
mph	miles per hour	1.61	kilometers per hour	km/h
		ACCELERATION		
ft/s^2	feet per $second^2$	0.30	meters per $second^2$	m/s^2
		TEMPERATURE (exact)		
°F	Fahrenheit	5/9[(Fahrenheit) - 32°C]	Celsius	°C

Approximate Conversions to English Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.39	inches	in
m	meters	3.3	feet	ft
km	kilometers	0.62	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
km^2	square kilometers	0.39	square miles	mi^2
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
		PRESSURE		
bar	bar	14.50	pounds per $inch^2$	psi
kPa	kilopascals	0.145	pounds per $inch^2$	psi
		VELOCITY		
km/h	kilometers per hour	0.62	miles per hour	mph
		ACCELERATION		
m/s^2	meters per $second^2$	3.28	feet per $second^2$	ft/s^2
		TEMPERATURE (exact)		
°C	Celsius	9/5 (Celsius) + 32°F	Fahrenheit	°F

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For the convenience of visually impaired readers of this report using text-to-speech software, additional descriptive text has been provided for graphical images contained in this report to satisfy Section 508 of the Americans With Disabilities Act (ADA).

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1.0 INTRODUCTION

1.1 Previous Research

In 2001, the National Highway Traffic Safety Administration (NHTSA) performed an evaluation of all known test maneuvers capable of potentially quantifying the on-road, untripped rollover resistance of light vehicles [1]. Most of these maneuvers used a programmable steering machine to command the respective steering inputs, however some used actual test drivers. Two such maneuvers were the ISO 3888 Part 2 (also known as the "ISO 3888-2" double lane change) and Consumers Union Short Course double lane changes.

Using up to five drivers per maneuver, NHTSA assessed the objectivity and repeatability, performability, discriminatory capability, and appearance of reality for each candidate maneuver. For each evaluation factor, the maneuvers received an adjectival rating ranging from Excellent to Very Bad. Due to the inherent variability associated with results obtained by human drivers, and the fact they were unable to excite "worst-case" responses from any of the four vehicles used in the study, both lane changes received low ratings in three of the four evaluation areas.

Although they were ultimately discarded in favor of the NHTSA Fishhook, the authors believe performing the ISO 3888-2 and Consumers Union Short Course lane changes was a worthwhile exercise. Conduct of these maneuvers provided useful data for many purposes, including an examination of human driver steering capability. Citing these capabilities has allowed NHTSA to defend many of the test maneuvers presently being performed by the Agency, including the NHTSA Fishhook and Yaw Acceleration Steering Reversal [2,3].

1.2. Source of the Data Used in the Report

The tests described in this study were a series of double lane changes performed as part of NHTSA's Light Vehicle Handling and Electronic Stability Control (ESC) Effectiveness Research Program [3]. When first conceived, the thrust of this program was to provide consumers with information to supplement the rollover resistance ratings already available via the Agency's New Car Assessment Program (NCAP). At the time these tests were performed, NHTSA was seeking to develop a test, or series of tests, capable of quantifying "good handling." It was envisioned that one way of potentially achieving this goal was to: (1) ask the drivers to respond to a questionnaire asking questions about how the vehicle responded to their inputs, and (2) use these subjective impressions to guide the development of objective test metrics (i.e., to evaluate maneuvers performed with a steering machine with a method based on the impressions of actual drivers).

While it is beyond the scope of this report to discuss the NHTSA's handling research, the authors believe it is useful to explain the origin of the data presented.

1.3 Scope of this Study

This report uses double lane change data collected during NHTSA's Light Vehicle Handling and ESC Effectiveness Research Program to document the steering capability of human drivers in a highly transient situation. Unlike maneuvers such as the NHTSA Fishhook, lane changes are path-following in nature, and therefore possess an inherently high appearance of reality. These are avoidance maneuvers that occur in the real world.

There are many different double lane change configurations used in industry. These include ISO 3888 Parts 1 and 2, the Consumer's Union short and long courses, and that presented to NHTSA by the Alliance of Automobile Manufacturers [4]. The data used in this study were collected during double lane changes based on the ISO 3888 Part 2 course, but with modifications to increase maneuver severity.

Three independent variables are investigated in this study: steering wheel angle (SWA), steering wheel rate (SWR), and steering wheel torque (SWT). The effect of driver, vehicle, and whether ESC was enabled or disabled on these variables is presented.

2.0 OBJECTIVES

In recent years, the use of programmable steering machines has become increasing common in the automotive testing community. NHTSA, most automakers, and many private organizations now have extensive experience with these machines, and their respective test programs presently rely on the accuracy, repeatability, and reproducibility automated steering is capable of delivering.

Although the benefits of a steering machine are readily apparent, it is important for users to understand that it is possible for the steering capability of some machines to exceed that of a human driver. This is especially important when designing maneuvers that endeavor to emulate a real world on-road driving scenario. Although a steering machine may possess the ability to input combinations of very large steering wheel angles and rates, maneuver severity should not be achieved by disregarding practical limitations[1]. Unfortunately, there is little contemporary research documenting what these limitations may be.

The objective of this study was to document the steering inputs of four experienced test drivers recorded during a series of double lane changes performed with modified ISO 3888 Part 2 course geometry. Specifically, steering wheel angle (SWA), steering wheel rate (SWR), and steering wheel torque (SWT) inputs are discussed. Additionally, the effect of driver, vehicle, and whether ESC was enabled or disabled on these variables is presented.

The drivers used in this study were not instructed to use exaggerated inputs for the sake of increasing the peak steering angles, rates, or applied torque values. During the time of test conduct, NHTSA had not anticipated the subsequent double lane change data would be used in the manner discussed in this report. The emphasis was on path following, not on the assessment of human driver steering capability. For this reason, the results discussed in this paper should not be taken to represent the absolute limit of a human performance. Rather, the authors present this information to help guide those developing maneuvers performed with automated steering; the data contained in this paper can be used to help researchers determine whether the steering demands imposed by a prospective test maneuver are reasonable.

[1] This is not to say a maneuver with inputs within the capabilities of a human driver cannot be severe. Although research has demonstrated the steering angles and rates associated with the NHTSA Fishhook maneuver can be attained by a human driver [1], the maneuver is capable of eliciting some of the most severe on-road responses seen by the Agency.

3.0 TEST CONDITIONS

3.1 Test Vehicles

A diverse range of test vehicles was used in this study, ranging from a high-performance sports car to a 15-passenger van. Each vehicle was equipped with an ESC. The authors believe the diversity of the vehicle fleet provides a reasonable representation of all light vehicles sold in the United States. This is important, since not all vehicles respond to driver steering inputs in the same manner, and are expected to impose different demands on the driver. For this reason, the authors believe the data collected during this study complement those collected during Phase IV of NHTSA's Light Vehicle Dynamic Rollover Research Program in 2001 [1]. Although the lane changes performed during Phase IV testing were performed with multiple test drivers, the vehicle fleet was comprised entirely of SUVs.

Each vehicle used in this study had been used in previous test programs, however each vehicle was originally purchased as new by NHTSA, and the respective suspensions were in excellent mechanical condition. Some basic descriptions of these vehicles are presented in Table 3.1.

Table 3.1. Test Vehicle Descriptions.

Vehicle	Classification and Misc. Features	Wheelbase (inches)	Mean Track Width (in)	Test Weight (lbs)	Steering Ratio (deg/deg)	Left Steer Lock (deg)	Right Steer Lock (deg)
2003 Toyota Camry	High-volume passenger car, ESC, FWD, V6, 5-spd auto, 4-dr	107.0	60.8	3790	17.3	531	582
2002 Chevrolet Corvette	Sports car; ESC, RWD, V8, 5-spd manual, hatchback	104.3	61.6	3489*	16.0	487	489
2004 Volvo XC90 4x4	SUV, ESC, RSC, AWD, T5, 5-spd auto, 4-dr, 7-passenger capacity	112.3	64.2	5209	16.0	485	475
2003 Toyota 4Runner 4x4	SUV, ESC, AWD, V6, 5-spd auto, 4-dr, 5-passenger capacity	109.9	62.2	4668	17.3	564	549
2004 GMC Savana 3500	15-passenger van, ESC, RWD, V8, 5-spd auto	155.5	68.2	7075	17.1	599	574

*Estimate based on known curb and instrumentation weights.

The measurements provided in Table 3.1 were taken with a Hybrid II anthropomorphic test dummy positioned in the driver's seat, titanium outriggers installed in lieu of the front and rear bumpers, instrumentation, and a full tank of fuel. NHTSA refers to this combination of test and safety equipment as the "Nominal Load" configuration.

3.2 Tires

Tires were of original equipment specification, and were inflated to the pressures recommended by the manufacturer on the respective placards. Each driver performed 10 lane changes with

ESC enabled, then ten tests with ESC disabled. Since two drivers shared one tire set, this means there were nominally 40 tests performed with each tire set. Since NHTSA's previous experience with double lane change testing indicated resulting tire wear was much less than that observed during tests such as the NHTSA Fishhook or J-Turn, the authors do not believe tire wear had a significant effect on this study's test outcome.

With the exception of the Chevrolet Corvette, inner tubes designed for radial tires were installed in each vehicle's tires to reduce the likelihood of tire debeading. Inner tubes were appropriately sized for the respective test tires. No lubricant was used when mounting tires to the rims used for testing. This was done to eliminate the possibility of tire lubricant contributing to debeading.

3.3 Load Configuration

All tests were performed with the vehicles in NHTSA's Nominal Load condition. With the exception of the Chevrolet Corvette, titanium outriggers were installed in lieu of the front and rear bumpers. Given the diversity of the vehicle pool, the authors believe results of this study should be reasonably representative of most light vehicles evaluated in the Nominal Load condition. All vehicles were evaluated with their respective ESC systems enabled and disabled. Each driver performed the disabled ESC tests prior to those performed with the systems enabled.

3.4 Test Surface

The tests described in this paper occurred during the period of June 18 through August 10, 2004. During this time, the VDA's peak coefficient of friction ranged from 0.93 to 0.95. The slide coefficient ranged from 0.83 to 0.88. The lowest ambient testing temperature was 61°F, recorded prior to a series of tests performed on June 30, 2004. The highest ambient testing temperature was 81°F, recorded prior to tests performed on July 12, 2004 and July 19, 2004.

3.5 Instrumentation

The test vehicles were similarly instrumented with sensors capable of measuring the following data: (1) vehicle speed, (2) steering wheel position and applied torque, (3) accelerations and rates about the vehicle's longitudinal, lateral, and vertical axes, linear rates, (4) chassis ride height, (5) lateral and longitudinal position on the test surface. These data were each recorded with an in-vehicle data acquisition system (DAS). Due to the narrow scope of this paper, only descriptions of sensors pertaining to steering and vehicle speed are provided. Descriptions of the other sensors and DAS, have been previously documented and are available in [1,5].

3.5.1 Steering Wheel Test Apparatus

Figure 3.1 shows the steering wheel test apparatus used for this study: an instrumented steering wheel, related hardware, and electronics. To facilitate measurement of the steering wheel angles and the torque applied by the driver, the vehicle's original equipment steering wheel was replaced with an instrumented wheel (upper right of Figure 3.1).

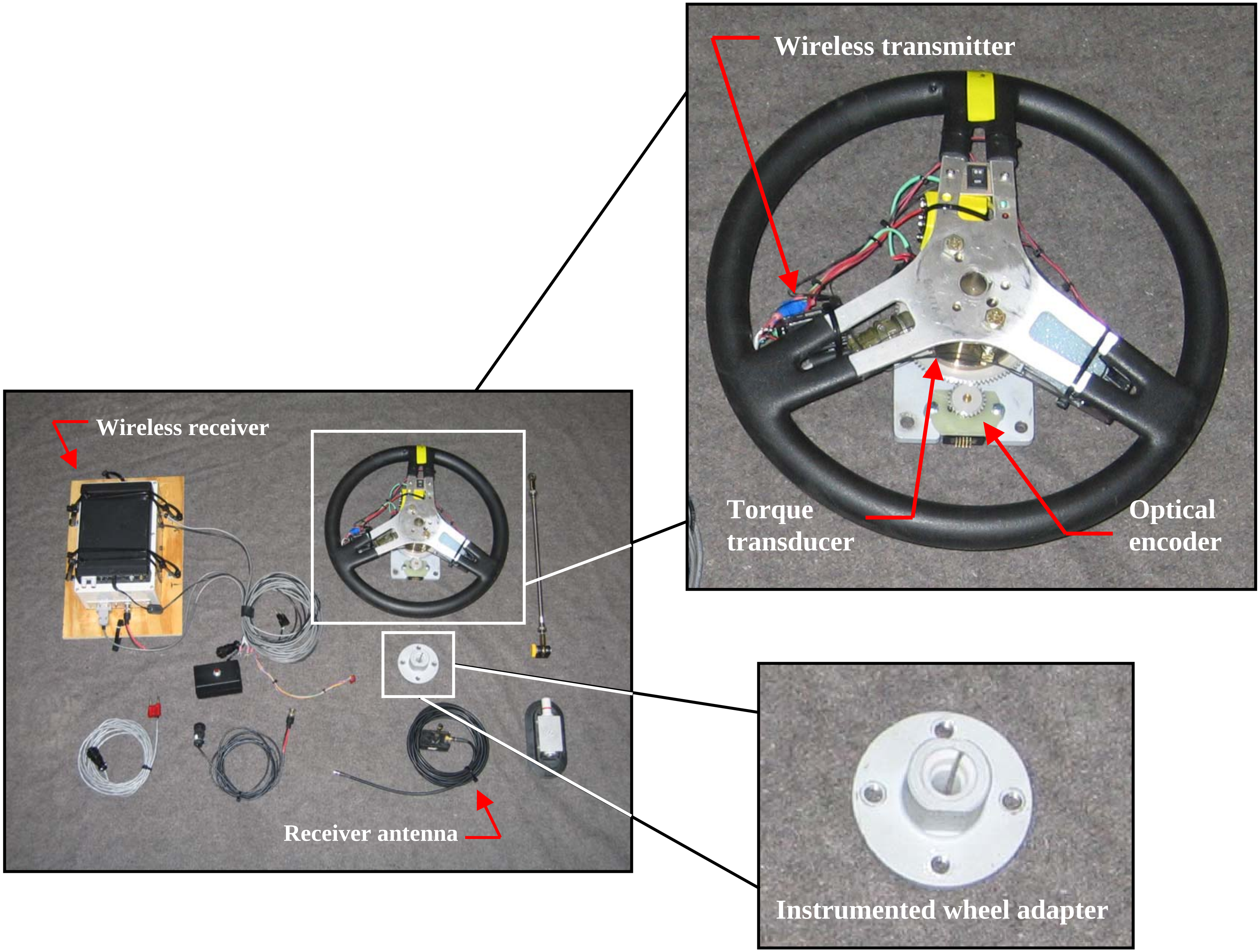

Figure 3.1. Steering wheel test apparatus.

A universal adapter was fabricated to allow the instrumented wheel to interface with each vehicle (lower right of Figure 3.1). The center of this adapter contained a replaceable plastic bushing that was driven onto the splines at the end of the steering column. To facilitate measurement of steering wheel position, the universal adapter was bolted to a 96-tooth gear securely attached to a three-spoke aftermarket steering wheel. This gear interfaced with an optical encoder. The encoder was attached to a back plate assembly that remained in a fixed position (with respect to the vehicle) at all times. This was accomplished via use of threaded rod, adjusted to a length that allowed one end of the rod to be attached to the encoder back plate, while the other end attached to a suction up attached to the vehicle's windshield.

To measure the torque applied by the driver during a lane change, the universal adapter was bolted to a torque transducer located between the 96-tooth gear and the three spoke steering wheel.

Although the steering angle data was sent to the DAS via conventional means, wireless transmission was used to send the applied torque data from the torque transducer to a receiver antenna mounted to the vehicle's dashboard. This was performed to avoid having wires from the torque transducer become tangled as the steering wheel was turned; a situation that could not only result in damage to the wires and/or sensors, but could also impair the ability of the driver to input their desired steering magnitudes. From the receiver, the torque data was sent to the DAS.

3.5.2 Vehicle Speed

Longitudinal vehicle speed was measured with a non-contact Doppler radar sensor placed at the center front of each vehicle. The sensor output was transmitted to the data acquisition system, to a display integral with the steering controller, and to a dashboard display unit.

4.0 TEST MANEUVER

A modified version of the ISO 3888-2 double lane change was used in this study. Although most features of the original ISO 3888-2 course (see Figure 4.1) were retained, past NHTSA testing indicated the length of the second lane compromised maneuver severity since it allowed time for the vehicle to settle before being directed to the final lane.

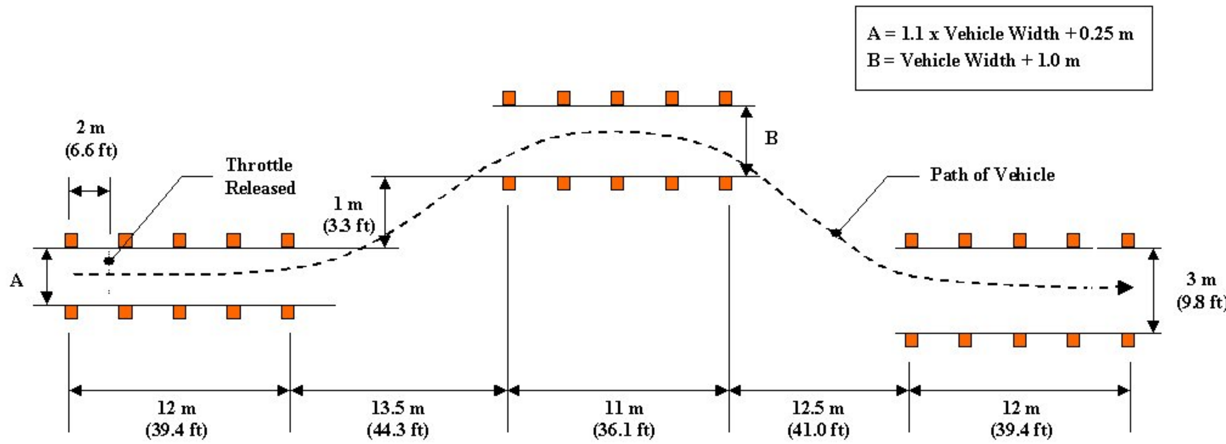

Figure 4.1. ISO 3888-2 course layout.

To maintain some of the desirable features of the ISO 3888-2 course (e.g., adjusting dimensions to the vehicle being evaluated), but with increased maneuver severity, the second lane was replaced with a gate comprised of only two pylons, as shown in Figure 4.2. Gate width remained a function of vehicle width, and was calculated in a manner identical to that specified by the "conventional" ISO 3888-2 process. Additionally, the lateral orientation of the gate to the left row of cones of the first and last lanes remained the same. However, the longitudinal distance from the end of the first lane to the entrance of the gate was set back 9-ft further than the entrance to the second lane of the conventional ISO 3888-2.

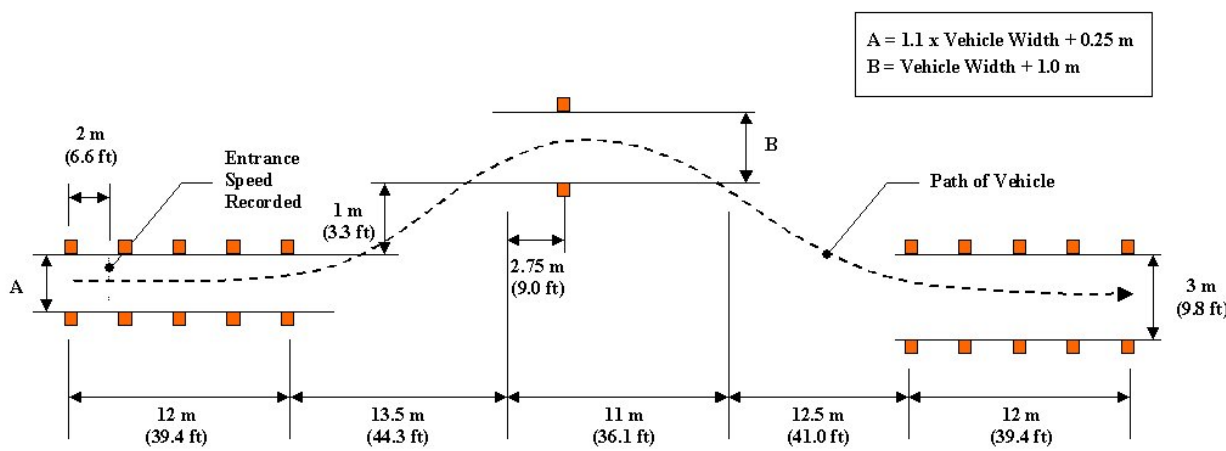

Figure 4.2. Modified ISO 3888-2 course layout.

Table 4.1 specifies what lane/gate widths were used for each vehicle. Due to the track width similarities of the Volvo XC90, Toyota 4Runner, and Chevrolet Corvette, the course layout used for these vehicles was held constant.

Table 4.1. Modified ISO 3888-2 Double Lane Change Lane/Gate Widths.

Vehicle	Vehicle Width (m)	Entrance Lane Width "A" (m)	Obstacle Gate Width "B" (m)
2004 GMC Savana 3500	1.98	2.43	2.98
2004 Volvo XC90 4x4	1.88	2.30	2.86
2003 Toyota 4Runner 4x4	1.85	2.30	2.86
2002 Chevrolet Corvette	1.82	2.30	2.86
2003 Toyota Camry	1.75	2.17	2.74

Four experienced drivers performed all double lane changes in this study. Each driver was male, and of average build (i.e., the authors do not believe the physical attributes of the drivers influenced the test results described in this paper). The ages of the drivers were: 26 (DE), 29 (BO), 31 (GF), and 64 (LJ). Each individual had prior test driver experience in past NHTSA test programs. Driver GF participates in motorsports competition, and driver LJ has been a TRC test driver for over 24 years.

To begin this maneuver, the vehicle was driven in a straight line at the desired entrance speed. Prior to entering the first lane, the driver released the throttle and, at a nominal distance of 6.6 ft (2.0 m) after entering the first lane, the maneuver entrance speed was recorded (as shown in Figure 4.2). No throttle input or brake application was permitted during the remainder of the maneuver. The driver steered the vehicle from the entrance lane, through the offset (left) gate, then through the exit lane.

Drivers iteratively increased maneuver entrance speed from approximately 35 mph. The iterations continued until "clean" tests could no longer be performed (the desired course could not be followed without striking or bypassing cones), however each driver was instructed to perform only ten tests per vehicle configuration. At the time the lane changes were performed, each driver was required to perform at least two "clean" runs using their maximum maneuver entrance speed. This was to facilitate later analyses (not related to the work described in this paper) that only considered clean test data.

To reduce any confounding effect that tire wear may have on the modified ISO 3888-2 double lane change results, a new tire set was installed on each vehicle after two drivers had completed their respective lane changes (i.e., two drivers shared one tire set).

5.0 TEST RESULTS

To quantify the drivers' steering capabilities, three inputs were considered: steering wheel angle, rate, and applied torque. The effects of driver, vehicle, and whether ESC was enabled or disabled on these inputs are discussed in this chapter. In the case of steering wheel rate and applied torque, the ability of a driver to sustain a particular input is also provided.

It is important to recognize that while the demands placed on the drivers during test track based double lane changes are very high, the authors believe the results presented in this report are still somewhat conservative. From the driver's perspective, the objective was to successfully complete the lane change without striking the course-delimiting cones or deviating from the confines of each lane or gate. The drivers were not instructed to use exaggerated inputs for the sake of maximizing the peak steering angles, rates, or applied torque values. To this end, the results discussed in this chapter should not be taken to represent the absolute limit of human performance. Rather, the data can be used to help researchers determine whether the steering demands imposed by a prospective test maneuver are reasonable.

5.1 Comments on the Statistical Analyses

To assess whether driver, vehicle, or ESC state (enabled or disabled) influenced the peak steering wheel angle, rate, or torque, a GLM model created in SAS was used to consider each factor. To improve the robustness of the model, the inclusion of a variety of interaction terms was considered. Ultimately, only one term, the interaction between ESC and vehicle, was included in the overall model.

Note: It is important to understand that the data used to create the model was comprised entirely of the overall maximum peak values (i.e., SWA, SWR, or SWT) recorded for each driver/vehicle/ESC test condition. In other words, although ten individual tests were performed by each driver for each condition, and each test contained multiple local peaks, only one value per test sequence was entered into the model—the overall maximum peak. The reasons for this approach were twofold. First, the focus of this paper was to discuss the maximum capabilities of the human driver (albeit one placed in a specific driving situation). Second, the data used for this evaluation were generated during tests not performed in an identical manner. As previously explained in Section 1.2, the tests providing the data used in this study were performed as part of a larger study designed to quantify light vehicle handling. One phase of this program required drivers to document their subjective impressions of the vehicle mentioned in this study (e.g., descriptions of responsiveness, controllability, predictability, etc.). To ensure an accurate overall impression of each vehicle was achieved, each driver experimented with different driving strategies within the ten lane changes performed within each driver/vehicle/ESC test condition. Although this approach allowed each driver to attain a good overall impression of each vehicle's handling characteristics, the resulting SWA, SWR, and/or SWT values observed within a particular test condition were somewhat disparate.

The authors do not believe the manner in which the tests were performed compromises the peak data discussed in this paper. Regardless of what driving strategy was used during a given test, all drivers attempted to successfully steer the vehicles through their respective lane changes during every test performed. While it is doubtful the driving situation used in this study was capable of capturing the absolute maximum capability of all human drivers (the authors believe a laboratory-based test capable of measuring the strength and dexterity of a large subject pool is better suited for such quantification), the fact the peaks discussed in this paper occurred during a driving situation constrained to the confines of a two-lane roadway greatly contributes to the face validity of the results reported in this paper. The authors believe reporting the overall peak values seen during each driver/vehicle/ESC test condition provides a reasonable way of concisely discussing the largest peak steering wheel angles, rates, and torques observed during the 400 lane changes from which the data were extracted.

5.2 Steering Wheel Angle

Steering wheel angle (SWA) refers to the position of the steering wheel measured from a known reference position. The reference position was established just prior to the initiation of the first primary steering input, not necessarily zero. In this report, three primary inputs are considered:

Initial Steer. Used to direct the vehicle from the exit of the first lane towards the cone-delimited gate.

Reversal #1. Used to direct the vehicle to and through the cone-delimited gate.

Reversal #2. Used to direct the vehicle to the entrance of the third lane.

Additional steering reversals were often used while the vehicle was being driven through the third lane to help settle the vehicle, especially during tests performed with ESC disabled. However, the magnitudes of these inputs were generally small when compared to those of the initial steer or either reversals. For this reason, these supplemental inputs are not discussed in this paper.

5.2.1 Maximum Values

Table 5.1 presents the overall peak SWA of each driver as a function of vehicle and ESC condition (i.e., whether the ESC was enabled or disabled). When ESC was enabled, three of the four drivers attained their largest SWA during tests performed with the Toyota 4Runner. Using this vehicle, drivers BO, DE, and GF achieved overall peak SWAs of 578, 517, and 540-degrees, respectively. The test containing the SWA peak of 578 degrees, the largest SWA observed in this study, is presented in Figure 5.1. With ESC enabled, driver LJ achieved an overall peak SWA of 399-degrees during a test performed with the Volvo XC90.

When ESC was disabled, three of the four drivers attained their largest SWA during tests performed with the GMC Savana. Using this vehicle, drivers BO, DE, and LJ achieved overall peak SWAs of 527, 435, and 343-degrees, respectively. With ESC enabled, driver GF achieved an overall peak SWA of 481-degrees during a test performed with the Chevrolet Corvette.

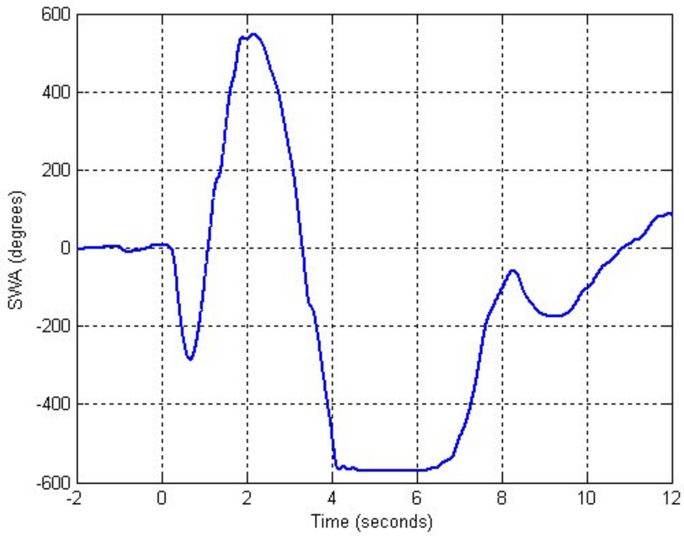

Figure 5.1. Steering wheel angles recorded during a Toyota 4Runner test performed by driver BO with ESC enabled. The overall maximum peak SWA (578 degrees) and overall maximum peak-to-peak SWA (1118 degrees) were recorded during this test.

Generally speaking, the overall peak SWA of each driver/vehicle/ESC configuration was higher with ESC enabled. In these cases, the SWAs recorded with ESC were between 2.1 and 59.3 percent greater with ESC enabled. That said, there was a total of six instances where the maximum handwheel angle recorded with ESC enabled was less than the respective input performed with ESC disabled: one for driver BO, one for driver DE, two for driver GF, and two for driver LJ. In these cases, the SWAs recorded with ESC were between 1.3 and 27.6 percent less than with ESC disabled.

Table 5.1. Overall Peak Steering Wheel Angles (degrees).

Vehicle	ESC Enabled				ESC Disabled			
	Driver BO	Driver DE	Driver GF	Driver LJ	Driver BO	Driver DE	Driver GF	Driver LJ
2004 GMC Savana 3500	568[2]	444[2]	357[2,3]	360[2]	527[2]	435[2]	367[2]	343[2]
2004 Volvo XC90 4x4	431[2]	448[2]	407[2]	399[2]	380[3]	284[3]	339[3]	290[2]
2003 Toyota 4Runner 4x4	578[3]	517[3]	540[2]	369[2]	515[2]	331[3]	339[3]	328[2]
2002 Chevrolet Corvette	349[2]	308[3]	376[3]	195[1]	482[3]	212[1]	481[3]	204[3]
2003 Toyota Camry	477[2]	355[2]	424[3]	312[2]	458[3]	402[3]	395[3]	316[2]

Note: [1]initial steer; [2]first steering reversal; [3]second steering reversal

To assess the statistical significance of the results presented in Table 5.1, the GLM model introduced in Section 5.1 was used. Specifically, the effects of ESC (enabled or disabled), vehicle, driver, and the interaction between ESC and vehicle on peak SWA magnitude were investigated. When all the peak values shown in Table 5.1 were compared, each of the four factors were found to have a statistically significant effect of peak SWA. The factors of driver and vehicle were highly significant at the 0.05 level, with respective p-values of <0.0001 and 0.0037. The effect of ESC, and the interaction between ESC and vehicle, were each marginally significant at the 0.05 level, with p-values of 0.0377 and 0.0419, respectively.

5.2.2 Maximum Peak-to-Peak Changes

Table 5.2 presents the overall peak-to-peak SWA of each driver as a function of vehicle and ESC condition. The magnitudes of two changes are considered: (1) the SWA from the initial steer peak to the first steering reversal, and (2) the SWA from the first to the second steering reversal. When ESC was enabled, each driver attained their largest peak-to-peak change in SWA during tests performed with the Toyota 4Runner. Using this vehicle, drivers BO, DE, GF, and LJ achieved maximum overall peak-to-peak changes of 1118, 908, 860, and 664-degrees, respectively. The test containing the peak-to-peak SWA peak of 1118 degrees, the largest peak-to-peak SWA observed in this study, was previously presented in Figure 5.1.

Table 5.2. Overall Peak-to-Peak Steering Wheel Angles (degrees).

Vehicle	ESC Enabled				ESC Disabled			
	Driver BO	Driver DE	Driver GF	Driver LJ	Driver BO	Driver DE	Driver GF	Driver LJ
2004 GMC Savana 3500	839[1]	759[2]	714[2]	622[1]	733[1]	747[2]	697[2]	643[2]
2004 Volvo XC90 4x4	674[1]	775[2]	699[1]	646[1]	722[2]	452[2]	570[2]	530[1]
2003 Toyota 4Runner 4x4	1118[2]	908[2]	860[2]	664[2]	941[2]	591[2]	619[2]	573[1]
2002 Chevrolet Corvette	653[2]	594[2]	657[2]	375[1]	789[2]	367[1]	738[2]	394[2]
2003 Toyota Camry	786[2]	650[1]	734[2]	555[2]	854[2]	666[2]	604[2]	534[2]

Note: [1]initial steer ⇨ first steering reversal; [2]first steering reversal ⇨ second steering reversal

When ESC was disabled, the consistency of the results degraded. For two of the drivers, the largest peak-to-peak change in SWA occurred during tests performed with the GMC Savana. Using this vehicle, drivers DE and LJ achieved maximum peak-to-peak values of 747 and 643-degrees, respectively. For driver BO, the largest peak-to-peak SWA was 941-degrees, recorded during a test performed with the Toyota 4Runner. Different still, driver GF's largest peak-to-peak SWA of 738-degrees was observed during a test performed with the Chevrolet Corvette.

Generally speaking, the overall maximum peak-to-peak SWA of each driver/vehicle/ESC configuration was higher with ESC enabled. In these cases, the SWAs recorded with ESC were between 1.6 and 71.5 percent greater with ESC enabled. In the seven instances where the maximum peak-to-peak SWA recorded with ESC enabled was less than the respective input performed with ESC disabled, the SWAs recorded with ESC were between 2.4 and 17.2 percent less than those seen with ESC disabled.

In a manner identical to that used in Section 5.1.1, the GLM model introduced in Section 5.1 was used to assess statistical significance of ESC (enabled or disabled), vehicle, driver, and the interaction between ESC and vehicle the peak-to-peak SWA magnitudes presented in Table 5.2. When all the peak values shown in Table 5.2 were compared, three of the four factors were found to have a statistically significant effect on maximum peak-to-peak SWA. The factors of driver and vehicle continued to be highly significant at the 0.05 level, with respective p-values of <0.0001 and 0.0009. The effect of ESC was a bit more pronounced (i.e., when compared to the effect of ESC on maximum peak SWA seen in Section 5.2.1), with a p-value of 0.0136. Interestingly, the interaction between ESC and vehicle was no longer significant at the 0.05 level, with a p-value of 0.1350.

5.3 Steering Wheel Rates

Steering wheel rate (SWR) is the change in steering wheel angle over time. To analyze the SWR used by each driver, four different filters were applied to the data during post-processing:

1. 6 Hz phaseless digital Butterworth
2. 500 ms running average, one-pass
3. 750 ms running average, one-pass
4. 1000 ms running average, one-pass

The use of two different filtering techniques is included in this paper for the sake of discussion. NHTSA typically applies the 6 Hz filter to data when a balance between reduced signal noise and preservation of peak magnitudes is desired. Applications where NHTSA believes use of a 6 Hz Butterworth filter is appropriate include the processing of linear accelerations, rates, and steering wheel angle.

A running average filter differs conceptually from the Butterworth variant; it reports the average value of the data over a user specified time interval. Applications where NHTSA believes use of running average filters is appropriate include wheel lift height, maximum lateral acceleration, and steering wheel rate.

When analyzing SWR data, it is important to consider the duration over which the rate was sustained. While it is not explicitly inappropriate to filter SWR data at 6 Hz, the peak values extracted from data filtered in this manner may have only been sustained for a matter of milliseconds. Since most test maneuvers occur over a longer period of time (i.e., they are not instantaneous), it is not appropriate to assume a driver capable of achieving high instantaneous SWRs can maintain them for extended intervals. This situation is remedied by using the running average filters with conservative interval durations.

5.3.1 Peak SWR Magnitudes

Table 5.3 presents the overall peak SWR calculated for each vehicle as a function of vehicle, post-processing filter, and ESC condition. To simplify the analysis used in this section, the SWR data is not broken down by driver, although the driver responsible for achieving the highest peak SWR per vehicle/data filter/ESC condition is indicated for the sake of completeness.

Table 5.3. Overall Peak Steering Wheel Rates (degrees/sec).

Vehicle	6 Hz (Butterworth filter)		500 ms (running average filter)		750 ms (running average filter)		1000 ms (running average filter)	
	ESC Enabled	ESC Disabled	ESC Enabled	ESC Disabled	ESC Enabled	ESC Disabled	ESC Enabled	ESC Disabled
2004 GMC Savana 3500	1603 (DE)	1525 (GF)	945 (BO)	944 (BO)	802 (BO)	793 (DE)	709 (BO)	710 (DE)
2004 Volvo XC90 4x4	1753 (GF)	1810 (GF)	943 (DE)	1095 (BO)	853 (DE)	889 (BO)	769 (DE)	721 (BO)
2003 Toyota 4Runner 4x4	1575 (GF)	1625 (BO)	1124 (BO)	1048 (BO)	931 (BO)	919 (BO)	836 (GF)	839 (BO)
2002 Chevrolet Corvette	1660 (GF)	1767 (GF)	1266 (GF)	1340 (GF)	854 (GF)	1189 (GF)	645 (BO)	963 (GF)
2003 Toyota Camry	1704 (GF)	1819 (DE)	1278 (GF)	1191 (DE)	1003 (GF)	1083 (BO)	714 (GF)	922 (BO)

The SWR data filtered with the 6 Hz Butterworth filter represents a conservative way of reporting instantaneous peak values. Since the peak values of the data processed with this filter occur over such a short time, their magnitudes can be quite large. With this filter, the overall peak rates across all vehicles ranged from 1525 to 1819 deg/sec. Note that the entire range of peak SWRs recorded during tests performed with ESC enabled (1575 to 1753 deg/sec) was contained within the ranges established by the ESC disabled tests (1525 to 1819 deg/sec). This trend was also seen for the SWA data processed with the 750 mph running average filter, and was very nearly true for data filtered with 500 and 1000 ms running average filters[2]. For this reason, it is not clear whether the presence of ESC may have influenced the peak SWRs used by the drivers.

As the aggressivity of the filter used to process SWR data was increased (i.e., the duration of the running average filter became longer), the magnitudes of the peak SWR data decayed. This is not surprising, as this essentially means the drivers were unable to sustain very large SWRs for long periods of time. That said, even when the SWR data were filtered with the 1000 ms running average filter, driver GF was able to achieve a peak rate of 963 deg/sec during a test performed

[2] The lower bound of the range of SWRs observed with ESC enabled was only 1 deg/sec lower than that established with ESC disabled.

with the Chevrolet Corvette. Figure 5.2 presents the SWRs observed during this test, processed with each of the three running average filters.

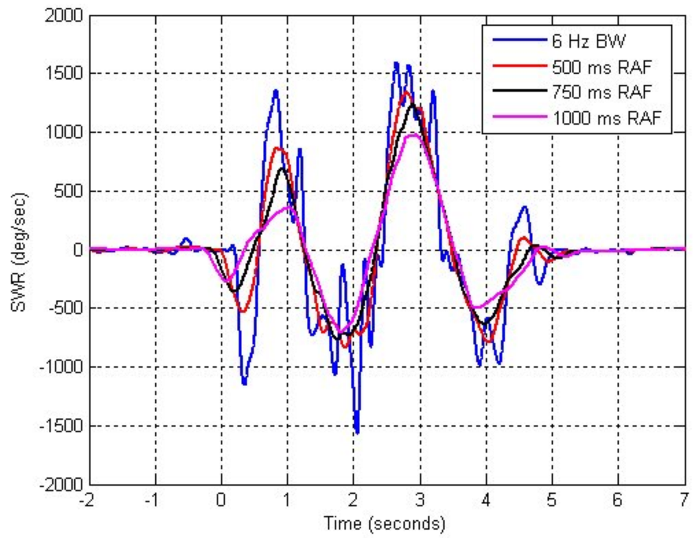

Figure 5.2. Steering wheel rates recorded during a Chevrolet Corvette test performed by driver GF with ESC disabled. Data processed with each of the four filters are compared.

5.3.2 Assessment of SWR Statistical Significance

To assess the statistical significance of the results presented in Table 5.3, the GLM model introduced in Section 5.1 was used. Specifically, the effects of ESC (enabled or disabled), vehicle, driver, and the interaction between ESC and vehicle on peak SWR magnitude were investigated. This analysis was performed on the data processed with each of the four filters to assess whether the drivers' ability to sustain[3] the peak values presented in Table 5.3 affected the significance of the results.

When the peak values generated with SWR data processed with the 6 Hz Butterworth filter were analyzed, only two factors were found to be statistically significant at the 0.05 level: driver ($p = 0.0002$) and vehicle ($p = 0.0485$). This trend continued when the data processed with the 500 ms running average filter were considered, with nearly identical p-values observed for driver ($p = 0.0002$) and vehicle ($p = 0.0479$).

As the duration of the running average filters were increased from 500 ms to 750 and 1000 ms, the effect of vehicle on peak SWR was no longer found to be significant at the 0.05 level. When the SWR data were processed with the 750 ms running average filter, the respective p-value was reduced to 0.0844; when the 1000 ms filter was used the p-value was reduced even further to 0.1559.

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[3] Since the running average filters used in this study report the average values seen during intervals defined by the filter duration, the authors believe the peak data shown in Table 5.3 provide a reasonable means of quantifying the "sustainability" of large SWRs.

5.3.3 Effect of Driver on Peak SWR

Since "driver" was the only factor that remained statistically significant regardless of filter type or duration, a more detailed breakdown of SWR as a function of driver was performed. The overall peak SWRs achieved by each driver is presented in Table 5.4. An indication of the vehicle used by each driver during the test containing the maximum peak SWR is also provided.

Table 5.4. Overall Peak Steering Wheel Rates Presented as a Function of Driver (degrees/sec).

Driver	6 Hz (Butterworth filter)		500 ms (running average filter)		750 ms (running average filter)		1000 ms (running average filter)	
	ESC Enabled	ESC Disabled	ESC Enabled	ESC Disabled	ESC Enabled	ESC Disabled	ESC Enabled	ESC Disabled
BO	1565[3]	1625[3]	1124[3]	1153[5]	931[3]	1083[5]	825[3]	922[5]
DE	1627[2]	1819[5]	958[5]	1191[5]	853[2]	943[5]	800[3]	718[5]
GF	1753[2]	1810[2]	1278[5]	1340[4]	1003[5]	1189[4]	836[3]	963[4]
LJ	1406[1]	1521[5]	822[2]	1007[5]	759[2]	751[1]	649[2]	608[1]

Note: [1]GMC Savana 3500, [2]Volvo XC90, [3]Toyota 4Runner, [4]Chevrolet Corvette, [5]Toyota Camry

When the peak SWR data for each driver, from each ESC/vehicle test condition, were processed with the 6 Hz Butterworth filter, only results from driver LJ were significantly different from those of the three other drivers at the 0.05 level (the p-values of the differences ranged from <0.0001 to 0.0453). When the peak SWR data processed with 500, 750, or 1000 ms running average filters were considered, only those tests performed by drivers LJ and BO, and drivers LJ and GF were statistically significant.

5.4 Steering Wheel Torque

To analyze the amount of torque applied by the driver to the steering wheel, the four filters used during processing of steering wheel rate (discussed in Section 5.2) were applied.

5.4.1 Peak SWT Magnitudes

The duration of the torque "spikes" containing the maximum peak SWTs were often short, therefore the filter type and duration (i.e., in the case of the running average filter) used during the post-processing of these data had a profound effect on the peak magnitudes. Table 5.5 presents the overall peak SWT calculated for each vehicle as a function of vehicle, post-processing filter, and ESC condition. In agreement with the process used to evaluate SWR, the SWT data is not broken down by driver, although the driver responsible for achieving the highest peak SWT per vehicle/data filter/ESC condition is indicated for the sake of completeness.

Table 5.5. Overall Peak Torques Applied to the Steering Wheel (lbf-ft).

Vehicle	6 Hz (Butterworth filter)		500 ms (running average filter)		750 ms (running average filter)		1000 ms (running average filter)	
	ESC Enabled	ESC Disabled	ESC Enabled	ESC Disabled	ESC Enabled	ESC Disabled	ESC Enabled	ESC Disabled
2004 GMC Savana 3500	32.2 (DE)	27.9 (DE)	17.9 (DE)	18.7 (BO)	13.2 (DE)	13.7 (BO)	10.2 (DE)	10.4 (BO)
2004 Volvo XC90 4x4	33.9 (DE)	29.3 (GF)	20.2 (DE)	11.7 (BO)	15.1 (DE)	8.4 (BO)	14.1 (DE)	6.4 (BO)
2003 Toyota 4Runner 4x4	29.8 (DE)	24.4 (DE)	15.7 (GF)	11.0 (GF)	12.6 (GF)	8.6 (GF)	10.8 (GF)	6.5 (GF)
2002 Chevrolet Corvette	28.5 (BO)	20.9 (DE)	11.9 (BO)	8.8 (LJ)	8.3, 8.3 (BO, GF)	7.8 (LJ)	7.1 (GF)	7.0 (LJ)
2003 Toyota Camry	23.9 (GF)	29.2 (BO)	16.9 (GF)	14.7 (BO)	12.1 (BO)	12.1 (BO)	9.1 (BO)	9.0 (BO)

When the SWT data presented in Table 5.5 was processed with the 6 Hz Butterworth filter, the overall peak SWTs across all vehicles ranged from 20.9 to 33.9 lbf-ft. However, perusal through these data, as well as those processed with the three running average filters, demonstrate substantial overlap of the data collected with ESC enabled and disabled. For this reason, it is not clear whether the presence of ESC may have influenced the peak SWTs used by the drivers.

The data presented in Table 5.5 indicate a human driver may perform maneuvers requiring 500 ms of continuous steering if the steering torque requirement is approximately 20.2 lbf-ft (27.4 N-m). This peak value was recorded during test performed by driver DE in the Volvo XC90, with ESC enabled. As the duration of the input requirement increases to 750 or 1000 ms, the ability of the driver to sustain high steering torque magnitudes was reduced. When these filters were applied to the test that produced the maximum peak SWT with the 500 ms running average filter, the maximum steering torque was reduced to 15.1 and 14.1 lbf-ft (20.5 and 19.1 N-m), respectively. These data further indicate drivers are unable to sustain large steering inputs for long periods of time. Figure 5.3 presents the SWTs observed during the Volvo XC90 test performed by driver DE for which each of the peak SWTs (i.e., for each of the four filters applied to the data) were achieved.

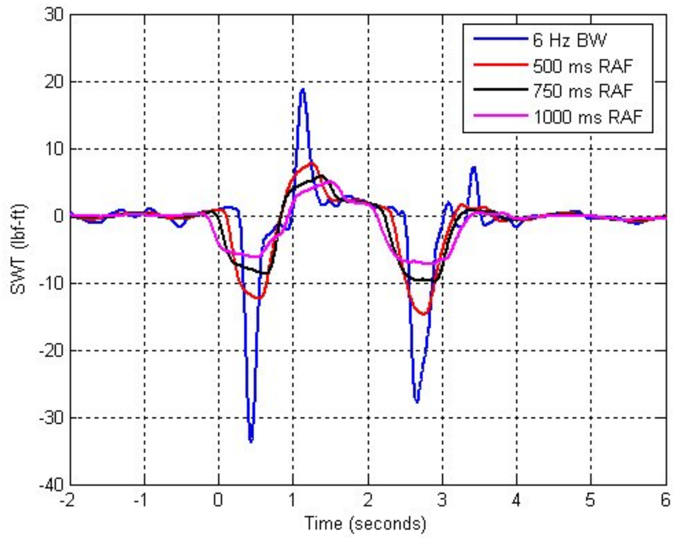

Figure 5.3. Steering wheel torques recorded during a Volvo XC90 test performed by driver DE with ESC enabled. Data processed with each of the four filters are compared.

5.4.2 Assessment of SWT Statistical Significance

To assess the statistical significance of the results presented in Table 5.5, the GLM model introduced in Section 5.1 was used. Specifically, the effects of ESC (enabled or disabled), vehicle, driver, and the interaction between ESC and vehicle on peak SWT magnitude were investigated. This analysis was performed on the data processed with each of the four filters to assess whether the drivers' ability to sustain[4] the peak values presented in Table 5.5 affected the significance of the results.

When the peak values generated with SWT data processed with the 6 Hz Butterworth filter were analyzed, each of the three main factors were found to be statistically significant at the 0.05 level: driver ($p = 0.0006$), whether the ESC was enabled or disabled ($p = 0.0397$), and vehicle ($p = 0.0085$). Interestingly, this trend changed as the duration of the running average filter increased. First, only the effect of ESC remained significant for all three filter durations, and there was a slight increase in significance as filter duration was extended from 500 ms ($p = 0.0224$) to 1000 ms ($p = 0.0115$). Second, the significance of vehicle decayed as the filter duration was lengthened from 500 ms ($p = 0.0054$) to 750 ms ($p = 0.0347$), and when processed with the 1000 ms running average filter, was no longer significant. Finally, the effect of driver was not significant when the peak SWT data were processed with any running average filter.

5.4.3 Effect of Driver on Peak SWT

The overall peak SWTs achieved by each driver is presented in Table 5.6. An indication of the vehicle by each driver during the test containing the maximum peak SWT is also provided.

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[4] Since the running average filters used in this study report the average values seen during intervals defined by the filter duration, the authors believe the peak data shown in Table 5.5 provide a reasonable mean of quantifying the "sustainability" of large SWTs.

Although the data for each filter used in this study are provided for the sake of completeness, it is important to remember the effect of driver on peak SWT was only found to be significant when the data were processed with the 6 Hz Butterworth filter.

When the peak SWT data for each driver, from each ESC/vehicle test condition, were processed with the 6 Hz Butterworth filter, only results from driver LJ were significantly different from those of the three other drivers at the 0.05 level (the p-values of the differences ranged from 0.0006 to 0.0056).

Table 5.6. Overall Peak Steering Wheel Torques Presented as a Function of Driver (lbf-ft).

Driver	6 Hz (Butterworth filter)		500 ms (running average filter)		750 ms (running average filter)		1000 ms (running average filter)	
	ESC Enabled	ESC Disabled	ESC Enabled	ESC Disabled	ESC Enabled	ESC Disabled	ESC Enabled	ESC Disabled
BO	28.5[4]	29.2[5]	13.2[5]	18.7[1]	12.1[5]	13.7[1]	9.1[5]	10.4[1]
DE	33.9[2]	27.9[1]	20.2[2]	18.2[1]	15.1[2]	13.2[1]	14.1[2]	10.2[1]
GF	31.0[2]	29.3[2]	16.9[5]	14.4[1]	12.6[3]	9.9[1]	10.8[3]	7.2[1]
LJ	24.2[2]	24.5[2]	12.3[1]	9.6[1, 2]	10.2[5]	7.8[4]	8.0[5]	7.0[4]

Note: [1]GMC Savana 3500, [2]Volvo XC90, [3]Toyota 4Runner, [4]Chevrolet Corvette, [5]Toyota Camry

5.5 Comparison with Previously-Collected Data

In 2001, NHTSA performed a series of tests to determine the best maneuver for evaluating dynamic rollover resistance [1]. In this work, NHTSA performed double lane changes with two well-known course configurations: the ISO 3888-2 and Consumers Union Short Course. In an attempt to ensure high maneuver severity and good repeatability, both of these lane changes were performed by three expert drivers. Four vehicles were used, and two were equipped with ESC.

Table 5.7 compares the data collected during the lane changes performed in 2001 with those data collected during the modified ISO 3888-2 lane changes performed for the study discussed in this paper. When comparing these results, it is important to recognized the data differ in a few ways:

1. The ISO 3888-2 and Consumers Union Short Course maximum SWA and SWR data were taken from valid tests only; tests where the driver was able to successfully drive through the course without striking any cones. This differs from the modified ISO 3888-2 lane change data previously presented in Section 5.2.1 in that the modified ISO 3888-2 lane change data considers all maximum peak SWAs. For these data, the ability of the driver to drive through the course was not a subject to any validity restriction.

2. The course layout of each double lane change was different; therefore they impose different demands on the drivers. The authors believe that of the three lane changes discussed in this section, the conventional ISO 3888-2 course is the least severe. In an attempt to reduce test variability, the ISO 3888-2 course designers constrain the path of the vehicle by requiring the width of the first and second lanes change as a function of vehicle width. A similar approach was used to establish the modified ISO 3888-2 course. Conversely, the Consumers Union Short Course relies on fixed course geometry.

Table 5.7. Past and Present Overall Peak Steering Input Comparison.

Course Layout	SWA (degrees)		SWR (deg/sec)					
			ESC Enabled			ESC Disabled		
	ESC Enabled	ESC Disabled	500 ms RAF	750 ms RAF	1000 ms RAF	500 ms RAF	750 ms RAF	1000 ms RAF
Modified ISO 3888-2 (Research presented in this paper)	578	527	1278	1003	836	1340	1189	963
ISO 3888-2 (Phase IV Rollover Research)	298	358	886	722	543	986	801	612
Consumers Union Short Course (Phase IV Rollover Research)	478	492	1030	822	784	1187	1026	831

In every condition, Table 5.7 demonstrates the greatest peak magnitudes of steering were used during the modified ISO 3888-2 lane changes, and that the peak Consumers Union Short Course steering magnitudes were always greater than those observed during the conduct of conventional ISO 3888-2 tests. These data suggest that while the results previously reported in [1] are certainly large, they are still somewhat conservative estimates of the steering potential offered by human drivers. For this reason, the authors believe that if the examination of maximum steering capability is of interest, experimenters must grant their subjects adequate real estate for it to be realized. In other words, although rigid course delimitation should theoretically improve steering input repeatability, it is likely the tight constraints will impede the driver's ability to exercise their true capabilities.

6.0 SUMMARY AND CONCLUSIONS

This report used double lane change data collected during NHTSA's Light Vehicle Handling and ESC Effectiveness Research Program to document the steering capability of human drivers in a highly transient situation. To achieve the best compromise between high maneuver severity and reasonably low path variability, modified ISO 3888 Part 2 lane change geometry was used.

Three independent variables were considered: steering wheel angle (SWA), steering wheel rate (SWR), and steering wheel torque (SWT). The effect of three factors (driver, vehicle, and whether ESC was enabled or disabled), and one interaction term (vehicle and ESC) on these variables was investigated.

A summary of the overall maximum peak values recorded during tests is presented in Table 6.1. The data presented in this paper clearly indicate drivers are capable of achieving very large steering inputs—even for relatively long periods of time. A maximum SWA of 578 degrees, and a maximum peak-to-peak SWA of 1118 degrees, were observed during an ESC enabled test performed with the Toyota 4Runner.

A maximum, instantaneous peak SWR of 1819 deg/sec was recorded during an ESC disabled test performed with the Toyota Camry. Even when filtered with the most aggressive filter used in this study, the data indicate it is possible for the human driver to sustain a SWR of 963 deg/sec for one second, witnessed during a ESC disabled test performed with the Chevrolet Corvette.

A maximum, instantaneous peak SWT of 33.9 lbf-ft (46.0 N-m) was observed during an enabled ESC test performed with the Volvo XC90. The ability of the driver to achieve high SWT was reduced greatly over time. In the extreme case where the driver is attempting to maintain the application of SWT for approximately one second, the largest peak SWT observed was 14.1 lbf-ft (19.1 N-m), 58.4 percent less than the maximum instantaneous peak value produced during the same test (albeit processed with a different filter).

Table 6.1. Summary of Overall Maximum Peak Values.

SWA (degrees)	Peak-to-Peak SWA (degrees)	SWR (degrees/sec)				SWT (lbf-ft)			
		6 Hz	500 ms RAF	750 ms RAF	1000 ms RAF	6 Hz	500 ms RAF	750 ms RAF	1000 ms RAF
578	1118	1819	1340	1189	963	33.9	20.2	15.1	14.1

Using the GLM procedure in SAS, the statistical significance of the three factors and one interaction was assessed. These analyses each indicate, to varying degrees, that different vehicles and/or vehicle configurations are capable of imposing different demands on the drivers. Each of the three primary factors, as well as the interaction between vehicle and ESC, were found to have a statistically significant effect on peak SWA at the 0.05 level. When maximum peak-to-peak SWA data were considered, the effect of driver, vehicle, and ESC remained statistically significant. The interaction between ESC and vehicle was not found to have a statistically significant effect on maximum peak-to-peak SWA.

The effect of driver on maximum peak SWR was the only factor that remained statistically significant regardless of filter type or duration. When the maximum peak SWR data processed with the 6 Hz Butterworth or 500 ms running average filters were considered, driver and vehicle were found to have a statistically significant effect at the 0.05 level. As the duration of the running average filters were increased from 500 ms to 750 or 1000 ms, only the effect of driver remained significant. The effect of vehicle on maximum peak SWR was not significant when the data were processed with 750 or 1000 ms running average filters.

When the peak values generated with SWT data processed with the 6 Hz Butterworth filter were analyzed, each of the three main factors were found to be statistically significant at the 0.05 level: driver, ESC, and vehicle. This trend changed as the duration of the running average filter increased in three ways. First, only the effect of ESC remained significant for all three filter durations. Second, the significance of vehicle decayed as the filter duration was lengthened from 500 ms to 750 ms, and when processed with the 1000 ms running average filter, was no longer significant. Finally, the effect of driver was not significant when the peak SWT data were processed with any running average filter.

Utility of Test Findings

This paper has presented the maximum steering capabilities of four human drivers. The authors hopes the research community will find a variety of applications for these data, however it is anticipated experimenters performing automated test maneuvers may find it the most useful (e.g., verifying commanded steering inputs are of “reasonable” magnitudes).

At the time this paper was written, only three programmable steering machine manufacturers were known to NHTSA: (1) AB Dynamics, (2) ATI / Heitz, and (3) SEA, Ltd. [6,7,8]. Table 6.2 summarizes the SWR and SWT limitations of each system. The data in this table suggest each machine should provide SWR magnitudes that exceed the capabilities of the four drivers considered in this paper. With the exception of the AB Dynamics SR30, each machine should also provide SWT magnitudes that exceed the capabilities of these drivers.

Table 6.2. Programmable Steering Machine Capabilities.

Manufacturer	Model	Maximum SWR	Maximum SWT
AB Dynamics	SR30	1000 deg/sec (if peak torque is required)	22.1 lbf-ft (30 N-m)
	SR60	1000 deg/sec (if peak torque is required)	44.3 lbf-ft (60 N-m)
ATI / Heitz	Sprint 3	1300 deg/sec (if peak torque is required)	36.9 lbf-ft (50 N-m)
SEA, Ltd.	ASC	720 deg/sec (if peak torque is required)	47.9 lbf-ft (65 N-m)

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