AN OVERVIEW OF NHTSA'S RECENT LIGHT VEHICLE DYNAMIC ROLLOVER PROPENSITY RESEARCH AND CONSUMER INFORMATION PROGRAM

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ABSTRACT

Thirty years ago, the National Highway Traffic Safety Administration (NHTSA) began studying the use of dynamic maneuvers to evaluate light vehicle rollover resistance. At that time, it was concluded the maneuvers being studied had such major problems, particularly in the area of objectivity and repeatability, that they could not be used by the Government to effectively rate rollover resistance. Today, following much effort, this is no longer the case. Using a small group of popular sport utility vehicles, NHTSA evaluated a comprehensive suite of eight maneuvers used to measure light vehicle dynamic rollover propensity. The Objectivity and Repeatability, Performability, Discriminatory Capability, and Appearance of Reality of each maneuver were assessed. These criteria have allowed NHTSA to identify what it now considered to be the best rollover resistance maneuvers.

This paper contains a brief assessment of three of the eight rollover resistance maneuvers evaluated during Phase IV of NHTSA's Light Vehicle Rollover Research Program.

INTRODUCTION

In Section 12 of the "Transportation Recall, Enhancement, Accountability and Documentation (TREAD) Act of November 2000" Congress directed NHTSA to "develop a dynamic test on rollovers by motor vehicles for a consumer information program; and carry out a program conducting such tests." This dynamic rollover resistance rating test is to be incorporated into NHTSA's New Car Assessment Program (NCAP).

The research described in this report was performed as part of NHTSA's effort to fulfill the requirements of the TREAD Act. Maneuvers used to assess on-road, untripped light vehicle dynamic rollover propensity were evaluated. Although on-road, untripped rollovers are responsible for only a small portion of the rollover safety problem for this classification of vehicles, there are enough fatalities due to these crashes that even a small portion of the problem equates to a substantial number of fatalities per year.

TEST VEHICLES, LOAD CONFIGURATIONS

Phase IV research used four sport utility vehicles: a 2001 Chevrolet Blazer, a 2001 Toyota 4Runner, a 2001 Ford Escape, and a 1999 Mercedes ML320. Two of these (the 4Runner and the ML320) were equipped with electronic stability control systems. Each vehicle was tested in up to three configurations: Nominal Load (which included the driver, instrumentation, and outriggers), Reduced Rollover Resistance (in which sufficient weight was placed on a test vehicle's roof to reduce its Static Stability Factor (SSF) by 0.05 from that of the baseline (as delivered from the dealer) plus outrigger load configuration[1]), and Modified Handling. Depending on the test vehicle, the Modified Handling configuration was achieved in one of two ways. The first technique was to load a vehicle to its rear Gross Axle Weight Rating (GAWR) while simultaneously achieving the Gross Vehicle Weight Rating (GVWR). The load was positioned so that changes to the vertical and lateral center of gravity positions were negligible; only the longitudinal location was altered. Alternatively, different tires/wheels available as OEM options for a particular vehicle were installed.

Table 1 presents the Static Stability Factors (SSF) of each vehicle in the Baseline, Nominal, Reduced Rollover Resistance, and Modified Handling configurations. Note that none of the Reduced Rollover Resistance SSF data include the effects of instrumentation. Although the Reduced Rollover

[1] A SSF reduction of 0.05 equates to a 1-star reduction in NHTSA's current static rollover resistance rating system for many sport utility vehicles. The weight on the roof was positioned so that the changes to the longitudinal and lateral position of the center of gravity were negligible.

Resistance SSFs of the Chevrolet Blazer and Ford Escape were measured directly, the SSFs of the Toyota 4Runner and Mercedes ML320 in this configuration were calculated from the Baseline Plus Outriggers configuration by summing moments about the vertical center of gravity. The actual, "as-tested" SSFs of the vehicles in the Reduced Rollover Resistance configuration are expected to be greater than those presented in Table 1 by amounts equal to the differences between the respective Nominal Load and Baseline Plus Outriggers conditions.

The Modified Handling SSFs of the ML320 and Escape were estimated based on the increased ride height predicted by comparing the outside diameter of the OEM wheel/tire package (i.e., that used in the Baseline, Nominal, and Reduced Rollover configurations) to that used in the Modified Handling Condition.

Table 1. Phase IV Static Stability Factors at Each Load Condition

Configuration	2001 Blazer	2001 4Runner	1999 ML320	2001 Escape
Baseline (as delivered)	1.025	1.098	1.123	1.232
Baseline Plus Outriggers	1.038	1.112	1.143	1.263
Nominal Load	1.048	1.122	1.175	1.267
Reduced Rollover Resistance	0.989	1.063	1.093	1.211
Modified Handling	1.054	1.123	1.177	1.226

TEST LOCATION

All Phase IV tests were performed on the Transportation Research Center Inc. (TRC) Vehicle Dynamics Area (VDA) located in East Liberty, Ohio. The test surface was paved with an asphalt mix used to construct many Ohio highways. All tests were performed on dry pavement. The average peak and slide coefficients of friction of the test surface were 0.95 and 0.84, respectively, over the period of testing.

DEFINITION OF TWO-WHEEL LIFT

In this paper the term "two-wheel lift" indicates that at least two inches of simultaneous lift of the inside wheels was observed during a particular test. Wheel lift less than two inches is not reported.

ROLLOVER RESISTANCE MANEUVERS

Eight Rollover Resistance maneuvers were evaluated during Phase IV, as shown in Figure 1. The maneuvers discussed in this paper are in bold.

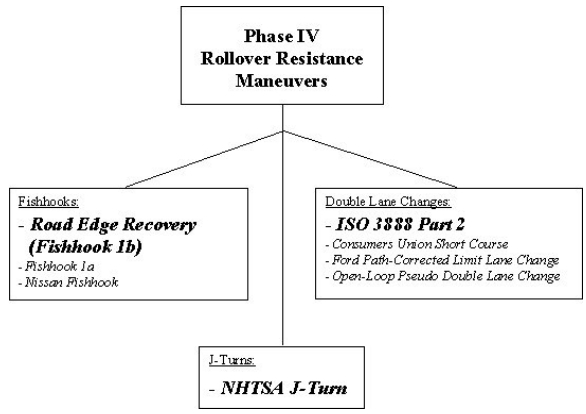

Figure 1. Phase IV Rollover Resistance maneuvers.

A programmable steering machine [3] was used to generate the handwheel inputs used for two maneuvers discussed in this paper, the J-Turn and Road Edge Recovery. Conversely, three test drivers input the required steering for the ISO 3888 Part 2 double lane change tests. Multiple drivers were used to monitor the repeatability of these inputs.

Depending on the maneuver, the test vehicles were evaluated with up to three configurations per maneuver (Nominal Load, Reduced Rollover Resistance, and Modified Handling).

MANEUVER EVALUATION CRITERIA

Phase IV research was an exploratory study of many test track maneuvers. The objective of this phase was to obtain the data needed to select a reduced set of maneuvers capable of characterizing light vehicle rollover resistance. Each Rollover Resistance maneuver was evaluated based on the following factors:

Objectivity and repeatability, i.e., whether the maneuver could be performed objectively with repeatable results for the same vehicle.

Performability, i.e., how difficult the maneuver was to objectively perform while obtaining repeatable results, how well developed the test procedures for each maneuver were, and whether the test procedure included adequate flexibility for adapting to differing vehicle characteristics.

Discriminatory capability, i.e., whether the maneuver demonstrated poorer performance for vehicles that have less resistance to rollover. Although of obvious importance, a maneuver's ability to discriminate between different levels of vehicle handling was not considered.

Appearance of reality, i.e., whether the maneuver might be performed by actual drivers while driving (particularly in emergencies). Appearance of reality was less important than the other three evaluation factors because NHTSA was more interested in what the vehicle was capable of doing. That said, NHTSA would like to use "worst case" maneuvers that drivers might actually perform.

For each evaluation factor, every rollover resistance maneuver received an adjectival rating ranging from Excellent to Very Bad. While the authors have tried to catalog the merits and possible problems of each maneuver, these ratings are subjective and could vary if judged by other technical evaluators. The adjectival ratings were assigned as follows:

Excellent. In the evaluated aspect, this maneuver is the best (or tied for best) of all of the rollover resistance maneuvers studied.

Good. In the evaluated aspect, this maneuver is substantially better than most, but not the best of the rollover resistance maneuvers studied.

Satisfactory. In the evaluated aspect, this maneuver is considered adequate for rating rollover resistance.

Bad. In the evaluated aspect, this maneuver is **not** considered adequate for rating rollover resistance because of a specific problem.

Very Bad. This maneuver has substantial problems for the particular evaluation factor. In the evaluated aspect, this maneuver is **not** considered adequate for rating rollover resistance.

MANEUVER DESCRIPTIONS AND RATINGS

Slowly Increasing Steer

The Slowly Increasing Steer maneuver was used to characterize the lateral dynamics of each vehicle, and was based on the "Constant Speed, Variable Steer" test defined in SAE J266 [4]. To begin this maneuver, the vehicle was driven in a straight line at 50 mph. The driver was instructed to maintain as constant a test speed as possible before, during, and after the steering inputs using smooth throttle modulation. At time zero, handwheel position was linearly increased from zero to 270 degrees at a rate 13.5 degrees per second, as shown in Figure 2. Handwheel position was held constant at 270 degrees for two seconds, after which the maneuver was concluded. The handwheel was then returned to zero as a convenience to the driver. The maneuver was performed to the left and to the right. Three repetitions of each test condition were performed.

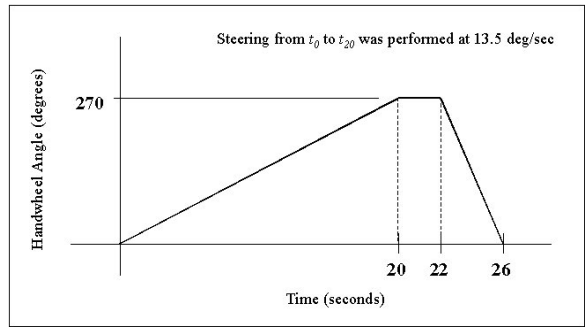

Figure 2. Slowly Increasing Steer maneuver description.

When lateral acceleration data collected during Slowly Increasing Steer tests was plotted with respect to time, a best-fit line was found to accurately describe the data from 0.1 to 0.4 g. The authors defined this as the linear range of the lateral acceleration response. Using the slope of the best-fit line, the average of handwheel positions at 0.3 g was calculated using data from each of the six Slowly Increasing Steer tests performed for each vehicle. This average handwheel position was used to calculate NHTSA J-Turn and Road Edge Recovery steering inputs, as described in later sections of this paper.

The handwheel input repeatability of the Slowly Increasing Steer maneuver was excellent. Vehicle speed input and test output repeatability was very good, but was strongly influenced by stability control intervention. The Slowly Increasing Steer maneuver is a Characterization maneuver, and therefore does not receive Rollover Resistance maneuver ratings.

NHTSA J-Turn

The NHTSA J-Turn was derived from the J-Turn used during NHTSA's Phase II rollover research program [5]. The handwheel magnitudes were calculated by multiplying the handwheel angle that produced an average of 0.3 g in the Slowly

Increasing Steer maneuver by a scalar of 8.0. The rate of the handwheel ramp was 1000 degrees per second. The J-Turn maneuver used automated steering inputs commanded by the programmable steering machine.

To begin the maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, coasted to the target speed, and then triggered the commanded handwheel input described in Figure 3. The nominal entrance speeds used in the J-Turn maneuver ranged from 35 to 60 mph, and were increased in 5 mph increments until a termination condition was achieved. Termination conditions included two-wheel lift or completion of a test performed at the maximum maneuver entrance speed without two-wheel lift. If two-wheel lift was observed, a downward iteration of vehicle speed was used in 1 mph increments until such lift was no longer detected.

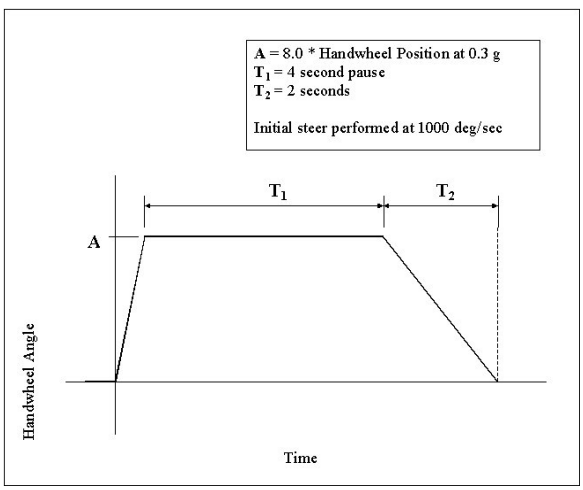

Figure 3. NHTSA J-Turn maneuver description.

A summary of the two-wheel lifts produced during J-Turn testing is presented later in the "Maneuver Comparisons" section of this paper. Using the evaluation factors previously described, the authors have rated the NHTSA J-Turn maneuver as follows:

Objectivity and Repeatability = Excellent

The NHTSA J-Turn was the most objective and repeatable of all of the Rollover Resistance maneuvers performed during Phase IV. By using the programmable steering machine, handwheel inputs were precisely executed and consistently replicated from run-to-run. The test driver was able to achieve maneuver entrance speeds within an average of ± 0.9 mph (1.9 percent) from the desired target speed.

Generally speaking the vehicle speed, lateral acceleration, and roll angle data observed during J-Turn tests were highly repeatable. That said, the roll angle repeatability of tests performed at a vehicle's tip-up threshold speed (the maneuver entrance speed for which two-wheel lift may or may not occur) was, at times, lower than that observed at other speeds. Even when nearly identical steering and speed inputs were achieved, small response fluctuations (due to test-to-test variability) were apparent. When a vehicle is operated at the tip-up threshold, these fluctuations can lead to large differences in roll angle. Note that this is the case for all maneuvers that endeavor to evaluate dynamic rollover propensity. As such, roll angle variability at the tip-up threshold did not lower the Objectivity and Repeatability rating of the J-Turn maneuver.

Performability = Excellent

The NHTSA J-Turn had one major steering input. As such, it was easiest of all of the dynamic rollover propensity maneuvers to perform. Objective and repeatable NHTSA J-Turns were easily performed using the programmable steering controller. The test procedure was well developed, and adapted handwheel input magnitudes to the vehicle being evaluated.

Discriminatory Capability = Excellent
(when limited to vehicles with low rollover resistance and/or disadvantageous load configurations)

None of the Phase IV test vehicles experienced two-wheel lift during NHTSA J-Turn tests performed in the Nominal Load configuration. However, all of the vehicles except the Ford Escape and the Toyota 4Runner (with its yaw stability control enabled) had two-wheel lift when tested in their Reduced Rollover Resistance configuration.

The NHTSA J-Turn is not a severe enough maneuver to discriminate between typical, current generation, sport utility vehicles loaded with a driver and passenger only (e.g., Phase IV vehicles in the Nominal Load configuration). However, it was sensitive to the decrease in rollover resistance attributable to a decrease in SSF of 0.05. Also the speed at tip-up could discriminate between the individual Phase IV test vehicles when the entire group was loaded to produce a decrease in SSF of 0.05. In Phase IV, a roof load of either 120 or 180

pounds was used to reduce the SSF by 0.05, but the addition of 5 to 6 passengers can cause a similar reduction in SSF for typical current generation SUVs, vans and pickup trucks.

Appearance of Reality = Good

Drivers can perform J-Turns during actual driving. Cloverleaf entrance/exit ramps and tightly curved roads driven at substantial speeds are two such examples. The NHTSA J-Turn was not given an excellent rating in this category, however, because it is very unlikely that actual drivers would input handwheel angles as large as those used in the J-Turn without also applying sustained braking. Braking introduces longitudinal wheel slip, and longitudinal wheel slip can greatly reduce lateral force. Since a reduction in lateral force has the effect of lowering the overturning moment of the vehicle, the likelihood of an on-road untripped rollover occurring (while the driver is engaged in sustained braking) is lessened.

During NHTSA's discussions with the automotive industry, every manufacturer stated that they routinely perform J-Turn testing during vehicle development. This maneuver has a long history of industry use.

Road Edge Recovery Maneuver

The Road Edge Recovery maneuver (also known as Fishhook 1b or the Roll Rate Feedback Fishhook) was derived from the Fishhook 1 maneuver used during Phase II. Unlike the Phase II fishhook, however, the initial and countersteer handwheel magnitudes were symmetric, and were calculated by multiplying the handwheel angle that produced an average of 0.3 g in the Slowly Increasing Steer maneuver by a scalar of 6.5. The duration of the maneuver dwell time (the time between completion of the initial steering ramp and the initiation of the countersteer) was not fixed. Road Edge Recovery dwell times were defined by the roll motion of the vehicle being evaluated, and could vary on a test-to-test basis. This was made possible by having the steering machine monitor roll rate (roll velocity). If an initial steer to the left was input, the steering reversal following completion of the first handwheel ramp occurred when the roll rate of the vehicle first equaled or went below 1.5 degrees per second. If an initial steer to the right was input, the steering reversal following completion of the first handwheel ramp occurred when the roll rate of the vehicle first equaled or exceeded -1.5 degrees per second. Road Edge Recovery maneuvers used automated steering inputs commanded by the programmable steering machine. The handwheel rate of the initial steer and countersteer ramps was 720 degrees per second.

To begin the maneuver, the vehicle was driven in a straight line at a speed slightly greater than the desired entrance speed. The driver released the throttle, coasted to the target speed, and then triggered the commanded handwheel input described in Figure 4. The nominal entrance speeds used for the Road Edge Recovery maneuver ranged from 35 to 50 mph and were increased in 5 mph increments until a termination condition was achieved.

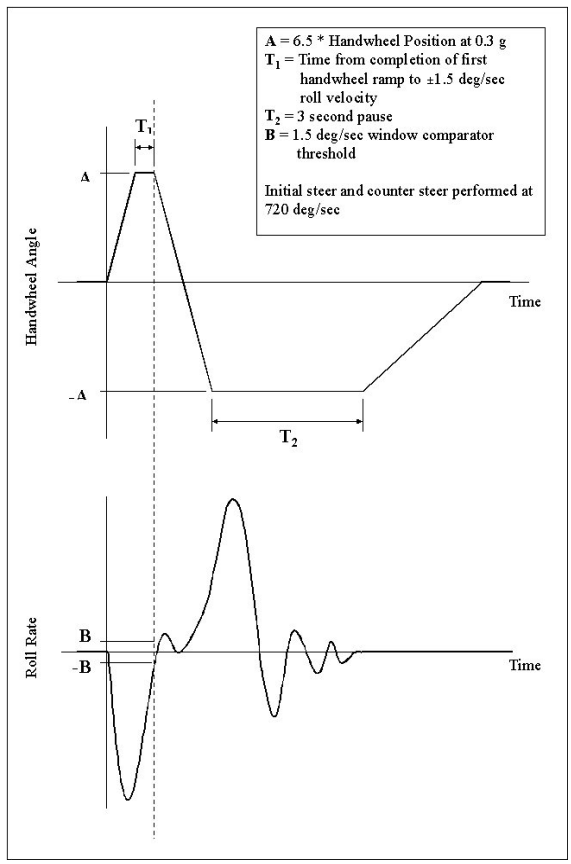

Figure 4. Road Edge Recovery maneuver description.

Road Edge Recovery termination conditions included two-wheel lift or completion of a test performed at the maximum maneuver entrance speed without two-wheel lift. If two-wheel lift was observed, a downward iteration of vehicle speed was used in 1 mph increments until such lift was no longer detected. Once the lowest speed for which two-wheel lift could be detected was isolated, two

additional tests were performed at that speed to monitor two-wheel lift repeatability.

A summary of the two-wheel lifts produced during Road Edge Recovery testing is presented later in the "Maneuver Comparisons" section of this paper. Using the evaluation factors presented previously, the authors have rated the Road Edge Recovery maneuver as follows:

Objectivity and Repeatability = Excellent

The Road Edge Recovery maneuver was performed with good to excellent objectivity and repeatability. By using the programmable steering machine, handwheel inputs were precisely executed and easily replicated from run-to-run. The test driver was able to achieve maneuver entrance speeds within an average of ± 1.3 mph from the desired target speed.

Generally speaking the vehicle speed, lateral acceleration, and roll angle data of Road Edge Recovery tests were highly repeatable. As stated before, the roll angle repeatability of tests performed at a vehicle's tip-up threshold speed (the maneuver entrance speed for which two-wheel lift may or may not occur) was, at times, lower than that at other speeds. Even when nearly identical steering and speed inputs were achieved, small response fluctuations (due to test-to-test variability) were apparent. When a vehicle is operated at the tip-up threshold, these fluctuations can lead to large differences in roll angle. Note that this is the case for all maneuvers that endeavor to evaluate dynamic rollover propensity. As such, roll angle variability at the tip-up threshold did not lower the Objectivity and Repeatability rating of the Road Edge Recovery maneuver.

The Objectivity and Repeatability of the Road Edge Recovery maneuver is slightly worse than that of an otherwise identical maneuver not using roll rate feedback. This is because using roll rate feedback to initiate Road Edge Recovery steering reversals can increase dwell time variability when certain combinations of handwheel angles, rates, vehicle speed, and load configuration are considered. Such combinations can influence the roll motion of the vehicle such that it differs from that observed during other tests performed in a particular series. Since the roll rate zero crossing immediately following completion of the initial steer defines when the handwheel reversal is initiated, a delayed roll rate zero crossing translates into an extended dwell time. If this occurs, preservation of the vehicle's roll motion can be compromised (even though the reversal still occurs when the vehicle achieves its post-initial steer maximum roll angle).

No anomalous roll rate zero crossings or inappropriately extended dwell times occurred during any valid Road Edge Recovery tests performed in Phase IV. However, the potential for such occurrences does exist. Efforts to prevent this phenomenon from influencing future test results are presently under development.

While the authors acknowledge the existence of this issue, it happens quite rarely (usually with heavily loaded vehicles). Since extended dwell times are obvious to the test driver, they may be instructed to perform an additional test with the same inputs to assess output repeatability, if required. Therefore, from a practical point of view, the objectivity and repeatability of this maneuver is not much worse from that of an otherwise identical maneuver not using roll rate feedback. For this reason, the authors assigned an Objectivity and Repeatability rating of Excellent to the Road Edge Recovery maneuver.

Performability = Excellent

Objective and repeatable Road Edge Recovery maneuvers were easily performed with the programmable steering controller. The test procedure was well developed and adapted handwheel input magnitudes to the vehicle being evaluated. Use of roll rate feedback allowed the timing of Road Edge Recovery handwheel inputs (i.e., the duration of the dwell time) to automatically adapt to a test conditions with differing maneuver entrance speed, load configuration, stability control intervention on a test-to-test basis.

Discriminatory Capability = Excellent

The Road Edge Recovery is an excellent maneuver for measuring the rollover resistance of different vehicles. Two-wheel lift was produced during tests performed with the Chevrolet Blazer and Mercedes ML320 (with enabled and disabled stability control) in the Nominal Load configuration. Each Phase IV vehicle tested in the Reduced Rollover Resistance configuration experienced two-wheel lift, regardless of whether its stability control was enabled or disabled (if so equipped).

Although the Mercedes ML320 was not evaluated in the Reduced Rollover Resistance configuration, the authors are certain it would have been exhibited two-wheel lift during tests performed in the this configuration. The Reduced Rollover Resistance configuration raises a vehicle's center of gravity height. This action will encourage, not prevent, two-wheel lift.

While the Road Edge Recovery maneuver does an excellent job of discriminating between different levels of untripped rollover resistance for typical, current generation, sport utility vehicles, it is unlikely the maneuver will be capable of such discrimination for the entire light vehicle fleet. The authors do not anticipate many incidents of two-wheel lift during testing of vehicles that have a Static Stability Factors of 1.13 or greater (e.g., vehicles that earn three or more stars under NHTSA's current rollover rating program). That said, the Road Edge Recovery is one of only two maneuvers known to NHTSA that causes two-wheel lift for vehicles above the 1.13 SSF range. Therefore, it does as well at discriminating throughout the entire fleet of vehicles as will any other on-road, untripped Rollover Resistance maneuver if the occurrence of two-wheel lift is used as a criterion.

Appearance of Reality = Excellent

The handwheel inputs defining any Road Edge Recovery (fishhook) maneuver approximate the steering a driver might use in an effort to regain lane position on a two-lane road after dropping the two passenger-side wheels off onto the shoulder.

ISO 3888 Part 2 Double Lane Change

The International Standards Organization (ISO) 3888 Part 2 Double Lane Change was a driver-based maneuver, i.e., the test driver closed the steering control loop. Since test driver generated steering inputs were used, three drivers were used for the evaluation of each vehicle. This allowed for the determination of the effects of driver variability. The programmable steering machine was not used to generate steering inputs for any path-following ISO 3888 Part 2 test.

The ISO 3888 Part 2 course was developed to observe the way vehicles respond to handwheel inputs drivers might use in an emergency situation. As shown in Figure 5, the course requires the driver to make a sudden obstacle avoidance steer to the left, briefly establish position in the left lane, and then rapidly return to the original [right] lane. The ISO 3888 Part 2 Double Lane Change sets the widths of the first and second lanes based on the width of the vehicle being evaluated.

To begin this maneuver, the vehicle was driven in a straight line at the desired entrance speed. At a nominal distance of 6.6 ft (2.0 m) after entering the first lane, the driver released the throttle. The maneuver entrance speed was determined when the driver released the throttle. 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) lane, then through the exit lane.

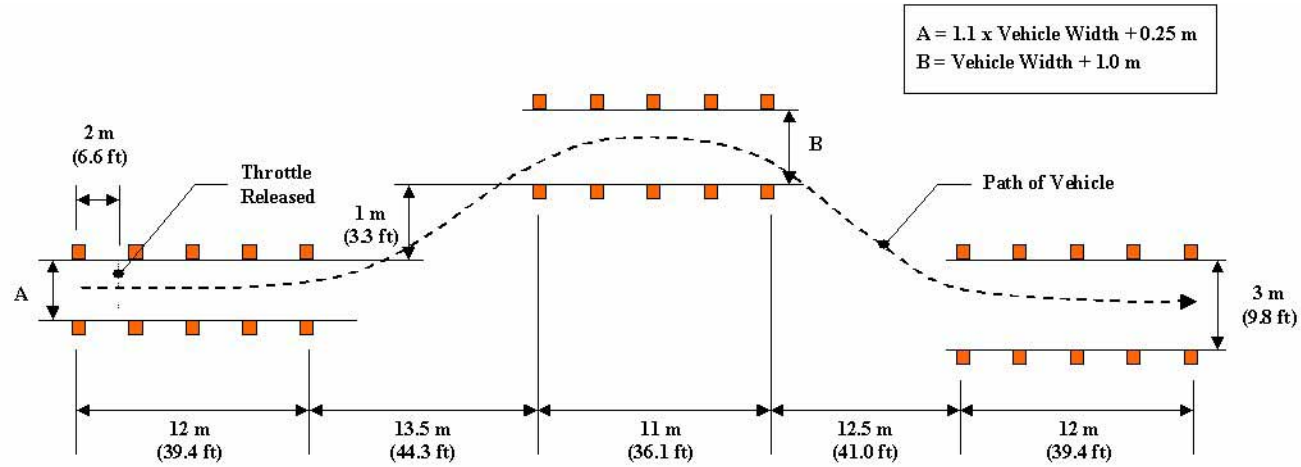

Figure 5. ISO 3888 Part 2 double lane change course dimensions.

Drivers iteratively increased maneuver entrance speed from approximately 35 mph in 1 mph increments. The iterations continued until "clean" tests could no longer be performed (i.e., the desired course could not be followed without striking or bypassing cones). Each driver was required to perform three "clean" runs at the their maximum speed. This was done to assess input and output variability for tests performed by the same driver, with the same entrance speed.

As suggested by the DaimlerChrysler Corporation, the rating metric used by NHTSA was the maximum maneuver entrance speed for which a driver successfully achieved a "clean" run (i.e., none of the cones delineating the course were struck or bypassed). Runs that were not "clean" were considered invalid. If a double lane change were to be used for determining Government dynamic rollover resistance ratings, the authors believe it is essential that the vehicle respect all course delineations.

The manner in which drivers chose to implement the 1 mph iterations was driver-dependent. Some drivers preferred to increase speed until they could no longer achieve a "clean" run. Once this threshold was reached, the driver would reduce speed slightly and perform three "clean" runs. Other drivers would perform three "clean" runs at one speed before proceeding to the next iteration. Both methods produced similar results. To reduce any confounding effect tire wear may have on ISO 3888 Part 2 Double Lane Change test results, new tires were installed on each vehicle for each driver.

The ISO 3888 Part 2 Double Lane Change tests were performed using test vehicles in their Nominal Load and Reduced Rollover Resistance configurations. No two-wheel lift was produced during any "clean" ISO 3888 Part 2 Double Lane Change, regardless of driver, vehicle, or load configuration. Using the evaluation factors presented previously, the authors have rated the ISO 3888 Part 2 Double Lane Change maneuver as follows:

<u>Objectivity and Repeatability = Bad</u>

Since the test driver generates steering inputs for the ISO 3888 Part 2 Double Lane Change maneuver, vehicle performance in this maneuver depends upon the skill of the test driver, the steering strategy used by the test driver, plus random run-to-run fluctuations. The ISO 3888 Part 2 course layout attempts to minimize this variability by using three cone-delineated lanes, and by relating the width of two of the three lanes to test vehicle width. These course layout differences endeavor to minimize the number of paths available to the driver while maintaining a high maneuver severity level.

Despite these attempts to minimize variability, substantial driver-to-driver and within driver run-to-run differences in the steering inputs occurred during the Phase IV ISO 3888 Part 2 testing. These differences tended to increase as the maneuver progressed. That said, these differences might not necessarily matter for the purpose of determining Rollover Resistance Ratings. What are most important are driver-to-driver and run-to-run differences in vehicle outputs, specifically how they influence the vehicle rating metric.

Using three test drivers, the overall range of maximum maneuver "clean" entrance speeds in the Nominal Load configuration varied from 1.1 mph for the Mercedes ML320 with disabled stability control, to 2.0 mph for the Chevrolet Blazer. The average range was 1.5 mph. While these may seem like small ranges, the entire range of maximum attainable "clean" entrance speeds was only 5.7 mph when all of the Phase IV vehicles were considered. Since the Phase IV vehicles are believed to be representative of contemporary sport utility vehicles, these results imply the maximum valid "clean" entrance speeds achievable for most sport utility vehicles will fall within this 5.7 mph range. Therefore, driver-to-driver variability accounts for an average of 27 percent of the rating metric range. The range of maximum "clean" entrance speeds of the Chevrolet Blazer suggests that this variability can account for up to 35 percent of the rating metric range.

Table 2 presents a rank ordering of the Phase IV rollover test vehicles based on the maximum "clean" entrance speeds achieved by the three test drivers. Note that "1" is the best rank and "6" the worst. This table clearly shows the problem caused by driver-to-driver variability combined with the small range of metric values. While the Chevrolet Blazer attained the best ranking from all three drivers, the rankings for the Ford Escape, Mercedes ML320 with stability control enabled, and the Toyota 4Runner with stability control enabled varied by three places (e.g., 2nd to 5th).

Table 2. Vehicle Rankings Based on Maximum Achievable Entrance Speeds for "Clean" ISO 3888 Part 2 Tests (Performed in the Nominal Vehicle Configuration)

Vehicle	Driver		
	GF/RS	LJ	RL
Chevrolet Blazer	1	1	1
Ford Escape	5	5	2
Mercedes ML320 (ESP)	2*	2	5
Mercedes ML320 (disabled ESP)	4*	3	3
Toyota 4Runner (VSC)	3*	3	6
Toyota 4Runner (disabled VSC)	6*	6	4

*Tests performed by Driver RS.

Driver skills and abilities vary with time. Although this was not directly measured in Phase IV, the authors believe that if the ISO 3888 Part 2 course was used to re-test the Phase IV vehicles, with the same drivers, the results would not be exactly reproduced. Since the rating metric range established in Phase IV was so narrow, day-to-day (or even hour-to-hour) changes in test driver performance could potentially change the maximum "clean" entrance speeds by a substantial percentage of the overall range.

Due to the problems associated with driver-to-driver variability and run-to-run (for the same driver) variability, the Objectivity and Repeatability of the ISO 3888 Part 2 Double Lane Change maneuver was rated as bad.

Performability = Good

The procedure for performing tests with the ISO 3888 Part 2 course was straightforward. However, as discussed above, use of this course is associated with objectivity and repeatability issues. Resolving these issues will add difficulty and complexity to the test procedure.

For example, one possibility for improving objectivity and repeatability is to use multiple drivers to perform the testing (three drivers were used during the NHTSA testing). While this should help, there are still potential problems. One exceptionally skilled test driver could generate very good performance metrics for a mediocre vehicle. If this exceptionally skilled driver did not test some other vehicle, that vehicle's performance metrics might, incorrectly, be lower than they should be. Therefore, in addition to using multiple drivers, procedures would need to be developed to ensure that drivers of approximately equal skill test every vehicle.

For the Government's purpose, the authors believe a test maneuver should adapt to differing vehicle characteristics so as to maximize severity. In the case of a double lane change, the course layout must be modified on a per-vehicle basis so as to achieve worst-case lane geometry. The ISO 3888 Part 2 Double Lane Change layout adjusts to the vehicle being tested. However, based on the fact two-wheel lift was not detected during any ISO 3888 Part 2 test for which no course delimiting cones were struck, the authors do not believe the layout imposes the worst-case lane geometry for any of the Phase IV vehicles.

Discriminatory Capability = Very Bad

ISO 3888 Part 2 tests were performed with each vehicle in the Nominal Load and Reduced Rollover Resistance configurations. Despite the use of high steering magnitudes and the production of high lateral accelerations, no two-wheel lift occurred during any "clean" run performed using the ISO 3888 Part 2 course, for any of the Phase IV test vehicles. While one instance of two-wheel lift did occur during a run that was not "clean," the rollover resistance rating of the vehicle was not adversely affected; when a run is not "clean", the path-following nature of the test is no longer meaningful. The driver could use an infinite combination of steering inputs. For example, rather than attempting to perform a "clean" run, the driver could input the Road Edge Recovery steering required to produce two-wheel lift. To achieve a high maneuver entrance speed, the driver could simply drive straight through the course without any avoidance steering. Either case would simply be recorded as a "not clean" test, although the test outcomes are obviously very different.

Unlike the J-Turn and Road Edge Recovery maneuvers, the occurrence/non-occurrence of two-wheel lift cannot be used as a measure of vehicle performance for this maneuver because two-wheel lifts during "clean" runs are unlikely to occur. Therefore, the rating metric used by NHTSA was the maximum entrance speed that a driver could successfully achieve during a "clean" run.

When tested in the Reduced Rollover Resistance configuration, vehicles had ballast placed on their roofs so as to raise their centers of gravity. Addition of the roof-mounted ballast reduced the Static Stability Factors of these vehicles by approximately 0.05. A 0.05 reduction in SSF equates, for sport utility vehicles, to approximately a one star reduction in the vehicle's rollover resistance rating. NHTSA believes that a one star reduction in the rating should make a vehicle substantially easier to roll over. Maneuvers with good discriminatory capability should measure substantially worse performance during Reduced Rollover Resistance tests, when compared with performance observed in the Nominal Load configuration.

Table 3 presents the maximum achievable "clean" entrance speeds attained by any of the test drivers for the Nominal Load and Reduced Rollover Resistance configuration for each test vehicle. When results from the two load configurations were compared, a substantial change in rollover resistance was not seen. While the maximum achievable "clean" entrance speeds attained by each test driver in the Reduced Rollover Resistance configuration did decrease slightly when compared to similar Nominal Load results for three vehicles, they increased slightly for the 2001 Toyota 4Runner. When each of the vehicles was considered, the overall average difference in maneuver entrance speed was 0.4 mph. The average of the absolute values of these differences was 1.3 mph. It is important to recognize that both average differences are less than the average driver-to-driver variability of 1.5 mph.

Table 3. Maximum Entrance Speeds Achieved by Any Driver During "Clean" ISO 3888 Part 2 Tests
(Nominal and Reduced Rollover Resistance Configurations)

Vehicle	Configuration		
	Nominal Load (mph)	Reduced Rollover Resistance (mph)	Difference (mph)
Chevrolet Blazer	41.0	39.0	**2.0**
Ford Escape	38.0	37.3	**0.7**
Mercedes ML320 (ESP)	38.0	37.4	**0.6**
Mercedes ML320 (disabled ESP)	38.9	37.1	**1.8**
Toyota 4Runner (VSC)	37.6	39.3	**-1.7**
Toyota 4Runner (disabled VSC)	37.0	38.0	**-1.0**

The substantial change in rollover resistance that was expected between the Nominal and Reduced Rollover Resistance configurations was not observed for the ISO3888 Part 2 Double Lane Change maneuver apparently because the sensitivity of the test to handling properties is predominant compared to its sensitivity to rollover resistance. Placing weight on a vehicle's roof raises its center of gravity, which reduces its rollover resistance. This also increases a vehicle's mass and roll moment of inertia, resulting in changes to a vehicle's handling that are not well understood. Since handling and rollover resistance are inextricably intertwined in the rating produced by this maneuver, the rating generated can improve while the rollover resistance of a vehicle deteriorates.

Results from both J-Turn and Road Edge Recovery testing are, also influenced by the handling characteristics of the vehicle. However, handling performance has less of a chance to dominate these maneuvers because they involve fewer major steering movements (one for a J-Turn, two for a Road Edge Recovery, and three for a Double Lane Change).

The above reasoning also explains an apparent anomaly in Table 3. In this table, the Nominal Load Chevrolet Blazer has the best ranking of any of the vehicles. However, based on its one star rating and performance in the NHTSA J-Turn and Road Edge Recovery maneuvers, the authors believe it has the lowest rollover resistance of any of the Phase IV rollover test vehicles [1]. The apparent contradiction is resolved if the ISO 3888 Part 2 Double Lane Change maneuver is regarded primarily as a measure of handling performance rather than rollover resistance.

Since tests using the ISO 3888 Part 2 Double Lane Change Course measure some combination of vehicle handling and rollover resistance (with handling characteristics apparently dominating the measured metric values), the authors can rate the Discriminatory Capability of the ISO 3888 Part 2 Double Lane Change maneuver for rollover resistance as no better than very bad.

<u>Appearance of Reality = Excellent</u>

In general, double lane change maneuvers have an excellent appearance of reality. The handwheel inputs used by the drivers during ISO 3888 Part 2 testing emulate the steering a driver might use in an

emergency obstacle avoidance maneuver performed on a two-lane road.

MANEUVER COMPARISONS

Two-Wheel Lift

Table 4 summarizes the incidents of two-wheel lift (or absence thereof) observed during J-Turn, Road Edge Recovery, and ISO 3888 Part 2 Double Lane Change testing. Nominal Load, Reduced Rollover Resistance, and Modified Handling data (where applicable) are each presented.

Table 4. Minimum Maneuver Entrance Speed Resulting in Two-Wheel Lift (mph)

Vehicle	J-Turn	Road Edge Recovery	ISO 3888 Part 2
2001 Chevrolet Blazer	-- (38.9[1])	40.1 (36.2[1], 34.9[2])	-- (--[1])
2001 Toyota 4Runner (VSC)	-- (--[1])	-- (49.6[1], --[2])	-- (--[1])
2001 Toyota 4Runner (no VSC)	-- (46.1[1])	-- (37.7[1], --[2])	-- (--[1])
1999 Mercedes ML320 (ESP)	-- (50.9[1])	49.9 (N/A[1], 51.7[2])	-- (--[1])
1999 Mercedes ML320 (no ESP)	-- (45.1[1])	46.4 (N/A[1], 51.3[2])	-- (--[1])
2001 Ford Escape	-- (--[1])	-- (46.0[1], --[2])	-- (--[1])

Note: Unless indicated, the results presented in this table were observed in the Nominal Load configuration.

[1]Reduced Rollover Resistance configuration

[2]Modified Handling configuration

For each vehicle, no two-wheel lift was observed during J-Turns or ISO 3888 Part 2 Double Lane Changes tests performed in the Nominal Load configuration. The Road Edge Recovery maneuver was capable of producing two-wheel lift for two vehicles evaluated in the Nominal Load configuration, the Chevrolet Blazer and the Mercedes ML320. In the case of the ML320, the Road Edge Recovery maneuver was able to induce two-wheel lift during tests performed with enabled and disabled stability control. The maneuver entrance speeds of the tests for which two-wheel lift occurred with enabled stability control were greater than those associated with disabled stability control.

No driver was able to produce two-wheel lift during "clean" ISO 3888 Part 2 tests performed with any vehicle in the Reduced Rollover Resistance configuration. However, two-wheel lift was observed during J-Turn and Road Edge Recovery tests performed with this load configuration. Compared to Nominal Load results, the Chevrolet Blazer produced two-wheel lift at lower entrance speeds in the Reduced Rollover Resistance configuration[2]. Unlike the Nominal Load configuration tests, NHTSA J-Turns performed with vehicles in the Reduced Rollover Resistance configuration produced two-wheel lift for every vehicle except the Ford Escape.

The NHTSA J-Turn produced two-wheel lift during Mercedes ML320 tests performed both with enabled and disabled stability control in the Reduced Rollover Resistance configuration. The entrance speeds of the tests for which two-wheel lift occurred with enabled stability control were greater than those of tests with stability control disabled. Similarly, the Road Edge Recovery maneuver produced two-wheel lift during Toyota 4Runner tests performed both with enabled and disabled stability control in this load configuration. The entrance speeds of the tests for which two-wheel lift occurred with enabled stability control were greater than those associated with disabled stability control.

The Modified Handling configuration imposed different demands on the vehicles depending upon how this test configuration was achieved. Installation of optional wheel/tire packages did not increase the rollover propensity of the Ford Escape or Mercedes ML320. Although two-wheel lift occurred during tests performed with the ML320, each of these tests began with maneuver entrance speeds greater than the 50 mph maximum nominal value. The Road Edge Recovery maneuver produced two-wheel lift during ML320 tests performed both with enabled and disabled stability control. Maneuver entrance speeds of the tests for which two-wheel lift occurred with enabled stability control were greater than those associated with disabled stability control.

[2]Road Edge Recovery tests were not performed with the Mercedes ML320 in the Reduced Rollover Resistance configuration due to test driver safety concerns. Since two-wheel lift occurred during Nominal Load configuration ML320 tests, the authors believe it would have certainly occurred in the Reduced Rollover Resistance configuration. The roof-mounted ballast used in this configuration reduced rollover resistance, thereby increasing rollover propensity compared to the Nominal Load.

Simultaneously loading the Toyota 4Runner to GVWR and rear GAWR did not adversely affect its rollover propensity. This loading had a very pronounced effect on the Chevrolet Blazer's rollover resistance; when left-right steering was input in this configuration, two-wheel lift occurred at a maneuver entrance speed of 34.9 mph.

Road Edge Recovery and J-Turn Maneuver Inputs vs. Closed-Loop Double Lane Change Steering

One of the most common criticisms of NHTSA's Road Edge Recovery and J-Turn maneuvers is that the handwheel inputs required to produce two-wheel lift are unreasonably large. It is important to acknowledge any maneuver that endeavors to directly assess on-road, untripped dynamic rollover propensity must include substantial steering inputs, especially if vehicle maneuver entrance speed is to be held to a reasonably safe level. To ascertain how the Road Edge Recovery and J-Turn handwheel inputs used in Phase IV related to those that occurred during tests performed by actual test drivers, maximum handwheel angles and rates were compared (a detailed discussion of the driver-based, closed-loop, path-following double lane changes performed in Phase IV is available in [1]).

Handwheel Angles

Some of the largest handwheel magnitudes observed during Phase IV research occurred during Consumers Union Short Course (CUSC) testing [1]. Although this paper does not discuss the CUSC course layout, test procedures, or test outcome, the maneuver is mentioned in this section because the steering data collected during these tests provides a more accurate depiction of what the capabilities of human drivers really are. This is because the course layout is not as tightly constrained as of the ISO 3888 Part 2, allowing the drivers much more flexibility in the manner in which they can steer vehicles through the course. Like the ISO 3888 Part 2, the CUSC was delineated with pylons. Phase IV CUSC testing used three drivers per vehicle.

For each vehicle, the handwheel angles observed during CUSC testing were up to 61.7 percent greater than those used to for J-Turns and up to 99.1 percent greater than those used to for the Road Edge Recovery maneuvers.

With the exception of the Mercedes ML320 with disabled stability control, the J-Turn handwheel angle magnitudes used for each vehicle were contained within the range established by the maximum handwheel magnitudes measured during CUSC and ISO 3888 Part 2 tests performed with that vehicle. For the ML320 with disabled stability control, the J-Turn handwheel magnitude was less than the maximum handwheel magnitude measured during either path-following, closed-loop, test.

The handwheel angle magnitudes used for the Road Edge Recovery maneuvers were all below the maximum handwheel magnitudes measured during the CUSC and ISO 3888 Part 2 tests performed with the same vehicle.

The maximum handwheel angle data presented in this section demonstrate that the magnitude of the inputs used to define the J-Turn and Road Edge Recovery maneuvers are within the capabilities of actual, albeit skilled, drivers. However, a meaningful comparison of J-Turn and Road Edge Recovery handwheel inputs to those that occurred during closed-loop, path-following double lane changes is incomplete without the consideration of steering rates, as discussed in the next section of this paper.

Table 5 summarizes the handwheel angles used during Phase IV J-Turn and Road Edge Recovery maneuvers, and those measured during CUSC and ISO 3888 Part 2 tests for which test drivers provided the steering inputs.

Table 5. Maximum Handwheel Angle Comparison: Automated Maneuvers Versus Closed-Loop Maneuvers (Nominal Load)

Vehicle	NHTSA J-Turn (degrees)	NHTSA Road Edge Recovery (degrees)	ISO 3888 Part 2 (degrees)	CUSC (degrees)
Chevrolet Blazer	401	326	358	492
Toyota 4Runner (VSC)	354	287	298	478
Toyota 4Runner (disabled VSC)			308	450
Mercedes ML320 (ESP)	310	252	262	400
Mercedes ML320 (disabled ESP)			323	411
Ford Escape	287	233	259	464

Handwheel Rates

When analyzing handwheel rate data, it is important to consider the duration over which the rate was sustained. While most drivers can generate very high handwheel rates, they are typically sustained for a short duration.

To assess whether the Phase IV test drivers could achieve the handwheel rates used by the J-Turn and Road Edge Recovery maneuvers, handwheel rates measured during the closed-loop, path-following double lane changes were processed with 500, 750, and 1000 millisecond running average filters during post-processing of the data. Using these data, the authors were able to determine whether an actual driver could sustain the handwheel rates required by a particular J-Turn or Road Edge Recovery maneuver for the required duration.

Table 6 compares the [fixed] handwheel rates used for the J-Turns and Road Edge Recovery maneuvers to sustained rates measured during CUSC and ISO 3888 Part 2 tests for which test drivers provided steering inputs

During CUSC testing, the Phase IV test drivers were able to sustain handwheel rates of up to 1187, 1026, and 831 degrees per second for 500, 750, and 1000 milliseconds, respectively. When ISO 3888 Part 2 data were considered, these rates fell to 986, 801, and 612 degrees per second, respectively.

The handwheel rate used for all J-Turn maneuvers performed in Phase IV was 1000 degrees per second. Since the steering angle magnitude of these maneuvers was vehicle dependent, the duration for which 1000 degrees per second had to be maintained ranged from 287 to 401 milliseconds. To assess whether the drivers used in Phase IV could achieve the handwheel rate used by the J-Turn, CUSC and ISO 3888 Part 2 data processed with the 500 millisecond running average filter were considered. The use of these data was most appropriate because its output was the average handwheel rate over a period of 500 milliseconds, slightly longer than that actually required for the J-Turn. Since handwheel rates of up to 1187 degrees per second were sustained by test drivers for 500 milliseconds during CUSC testing, the authors believe that the steering rate used by the J-Turn maneuver is within the capabilities of an actual driver.

The handwheel rate used for all Road Edge Recovery maneuvers performed in Phase IV was 720 degrees per second. Once again, since the steering angle magnitude of these maneuvers was vehicle dependent, the duration for which 720 degrees per second had to be maintained ranged from 647 to 906 milliseconds. To assess whether the drivers used in Phase IV could achieve the handwheel rate used by the Road Edge Recovery maneuvers, CUSC and ISO 3888 Part 2 data processed with the 750 and 1000 millisecond running average filters were considered.

Table 6. Maximum Handwheel Rate Comparison: NHTSA Maneuvers Versus Closed-Loop Maneuvers (Nominal Load)

Vehicle	J-Turn		Road Edge Recovery		ISO 3888 Part 2 (deg/sec)			Consumers Union Short Course (deg/sec)		
	Rate (deg/sec)	Duration (ms)	Rate (deg/sec)	Duration (ms)	500 ms RA	750 ms RA	1000 ms RA	500 ms RA	750 ms RA	1000 ms RA
Chevrolet Blazer	1000	401	720	906	986	801	612	1187	1026	831
Toyota 4Runner (VSC)		354		797	886	722	543	1030	822	784
Toyota 4Runner (disabled VSC)					800	660	535	989	815	768
Mercedes ML320 (ESP)		310		700	820	671	476	941	787	693
Mercedes ML320 (disabled ESP)					857	678	536	964	828	668
Ford Escape		287		647	807	682	454	1049	911	766

For the Mercedes ML320 and Ford Escape, use of data processed with the 750 millisecond filter was most appropriate because its output was the average handwheel rate over a period of 750 milliseconds; slightly longer than the 647 to 700 milliseconds duration actually required for the Road Edge Recovery tests performed with these vehicles. For the Chevrolet Blazer and Toyota 4Runner, use of data processed with the 1000 milliseconds filter was most appropriate because its output was the average handwheel rate over a period of 1000 milliseconds; slightly longer than the 797 to 906 millisecond duration actually required for the Road Edge Recovery tests performed with these vehicles. The authors believe that because handwheel rates of up to 1026 and 831 degrees per second were sustained for 750 and 1000 milliseconds, respectively, during CUSC tests, the steering required by the Road Edge Recovery maneuvers is within the capabilities of an actual driver.

SUMMARY AND CONCLUSIONS

Thirty years ago, NHTSA began studying maneuvers intended to assess dynamic rollover propensity. At that time, the conclusion was that the maneuvers being studied had such major problems, particularly in the area of objectivity and repeatability, as to preclude their use for discriminating rollover resistance. Today, following much effort, this is no longer the case. Table 7 summarizes the scores assigned to each Rollover Resistance maneuver in the areas of Objectivity and Repeatability, Performability, Discriminatory Capability, and Appearance of Reality.

Table 7. Summary of Rollover Resistance Maneuver Scores

Assessment Criterion	NHTSA J-Turn	Road Edge Recovery	ISO 3888 Part 2
Objectivity and Repeatability	Excellent	Excellent	Bad
Performability	Excellent	Excellent	Good
Discriminatory Capability	Excellent*	Excellent	Very Bad
Appearance of Reality	Good	Excellent	Excellent

*When limited to vehicles with low rollover resistance and/or disadvantageous load configurations.

As can be seen from Table 7, two of the Rollover Resistance maneuvers discussed in this paper have ratings of satisfactory or better in each of the four maneuver evaluation factors. In the authors' opinion, these two maneuvers are good for discriminating rollover resistance.

The authors do not believe driver-based double lane changes such as the ISO 3888 Part 2 are acceptable of effectively assessing a vehicle's rollover resistance.

The authors consider the Road Edge Recovery to be the best maneuver for measuring light vehicle rollover resistance. However, since the NHTSA J-Turn is the most basic rollover resistance maneuver (i.e., a single step-steer input), the authors feel it serves as a useful complement to the Road Edge Recovery.

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