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## ABSTRACT

Recent rollover resistance test results show discrepancies between vehicles steered with programmable steering machines and those steered by test drivers. This paper examines the differences in steering profiles and their effects on vehicle dynamics. For decades, test drivers have steered vehicles through rollover resistance test maneuvers. Human inputs, however, can cause variability from test to test. The National Highway Traffic Safety Administration (NHTSA) is currently performing rollover testing with steering machines in an effort to objectively rate the rollover resistance of passenger vehicles. The trapezoidal steer inputs are visibly different from human inputs and may be responsible for test differences. The roll rate feedback loop, which determines steer timing, may also affect vehicle response.

## BACKGROUND

Researchers have used test drivers to measure rollover resistance for decades. The objective of most rollover tests is to determine whether or not a vehicle will roll over on dry pavement when subjected to a combination of lateral forces and roll momentum. Driver controlled steering angles and rates can cause test result variability, especially in maneuvers that involve more than two steer inputs [1].

The National Highway Traffic Safety Administration (NHTSA) has recently determined that it will use an automatic steering machine [4] to test for rollover resistance in its New Car Assessment Program (NCAP) [6]. The chosen maneuver involves two steers and is called the fishhook. The steering machine is programmed to steer at a linear rate of 720 degrees per second. The steering wheel is accelerated as fast as the machine can get to this specified rate.

The NHTSA steering protocol uses a programmed feature called a roll rate feedback loop to time the delay between steers in accordance with the vehicle's roll behavior. Roll momentum for a two-steer maneuver is greatly affected by steering transition timing. Maximum roll momentum is achieved by timing the second steer input so that it coincides with the exact moment that the vehicle's body reaches its peak roll angle caused by the first steer input. NHTSA's chosen roll rate feedback will ideally control the timing of steers so that each vehicle will experience its worst case accident scenario.

The chosen NHTSA fishhook test is the result of extensive research to determine a repeatable test designed to evaluate rollover propensity. A vehicle that does not tip up in this maneuver is not necessarily immune to untripped rollover. The current program using the fishhook maneuver has had a great safety benefit on current model SUVs and light trucks.

NHTSA has studied the problem of test repeatability and severity for decades and feels that their recently chosen protocol addresses these issues. Recent rollover resistance test results by NHTSA [3] show some differences with those performed by researchers using test driver inputs. This paper examines differences between NHTSA's steering protocol vs. test driver inputs and how they can affect vehicle response.

## ROLL RATE ANALYSIS

Study of vehicle roll behavior shows that steer input timing can affect resulting body roll magnitude. For a two-steer maneuver, if the second steer is input too quickly or too slowly, the magnitude of the second body roll angle will not be worst case. Worst case roll behavior will occur if the second steer is timed so that it begins to take effect just as the vehicle's sprung mass stops rotating.

Automotive Testing, Inc. has developed a roll rate feedback loop, which triggers the second steer when the roll rate from the first steer crosses zero. There is a timing delay between the zero crossing and the second steer input on the order of 0.1 to 0.15 seconds.

An example of roll rate and steering input are shown in Figures 1 and 2. The steering is reversed at or about the time the roll rate crosses zero (at about 0.9 seconds). The horizontal axis is time (sec) and the vertical axis is degrees per second for roll rate and degrees for steer angle.

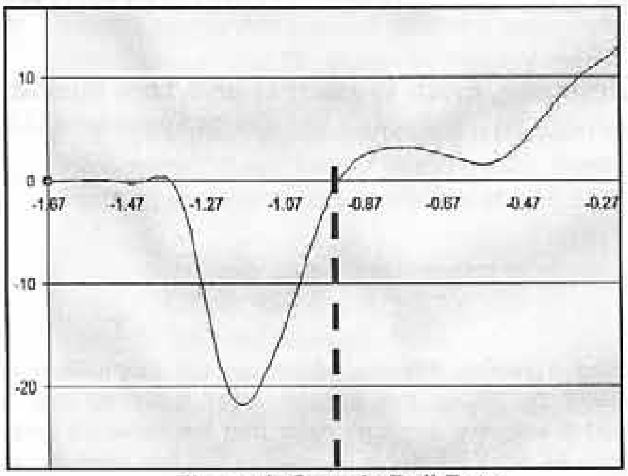



**Figure 1: Sample Roll Rate**

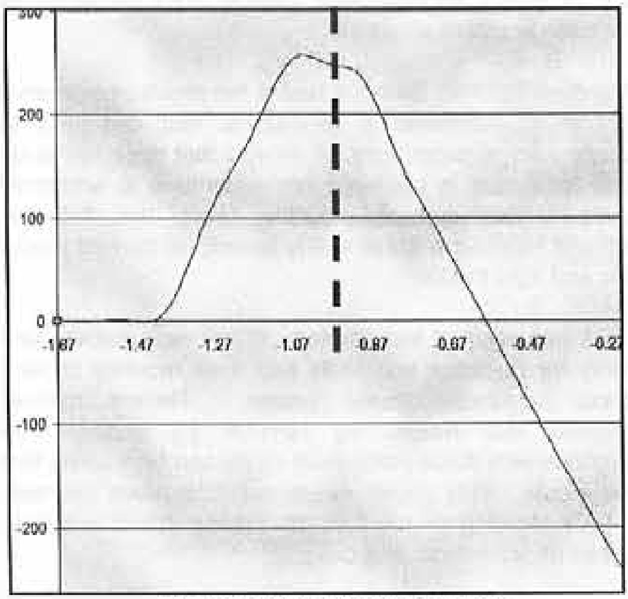



**Figure 2: Sample Steer Angle**

## HUMAN STEER TEST RESULTS

A stock condition unloaded 1997 Ford Explorer 4-door 4x4 was tested with a two steer maneuver [5]. The vehicle was tested through nine runs without occurrence of major two wheel lift (wheel lift that would likely result in untripped rollover). The steering transition time for each of these runs was short.

The Graphs in Figures 3-5 show that for the three most severe of these runs (steering/speed combination), the vehicle's roll angle due to the first steer input pauses before ultimately decreasing as the vehicle is steered in the opposite direction. The peak resulting roll angle due to the second steer was only 8 degrees, which is about the point of minor wheel lift (for reference, the horizontal axis is time and the vertical axis is degrees of roll). The entry speed for each of these runs was 57.6 mph. The vertical axis is angle in degrees and the horizontal is time (sec).

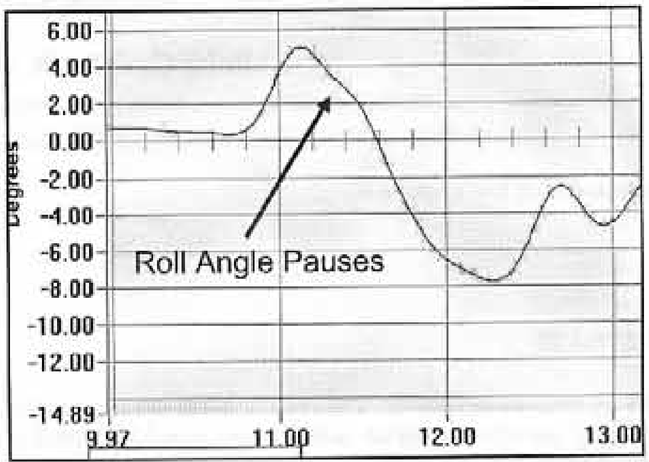



**Figure 3: Run Number DSM14 (57.6 mph)**

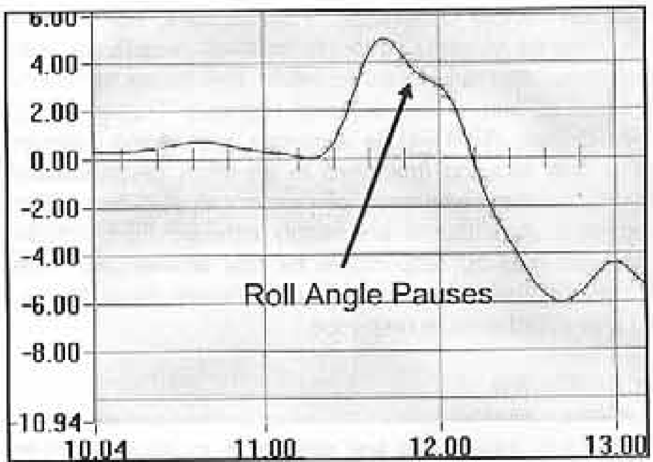



**Figure 4: Run Number DSM15 (57.6 mph)**

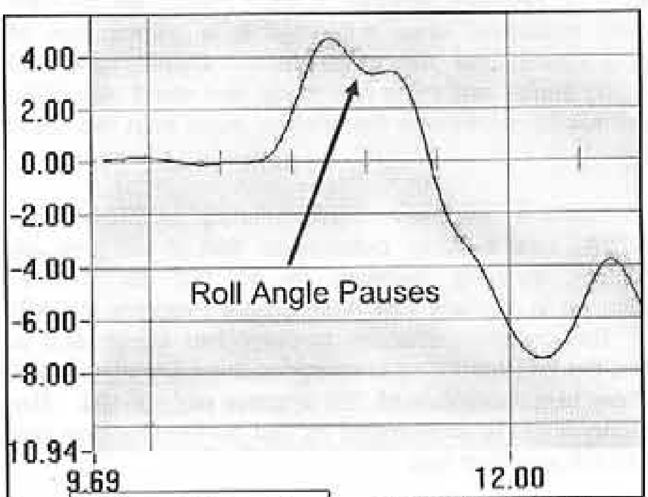



**Figure 5: Run Number DSM16 (57.6 mph)**

The same vehicle was then tested under the same conditions with a delayed steering transition time (on the order of 0.1 to 0.2 seconds longer). The handling result was drastically different. The vehicle rolled onto its outriggers violently three consecutive times. Figures 6 and 7 show the steering profiles for both run groups (non-tip-up and tip-up).

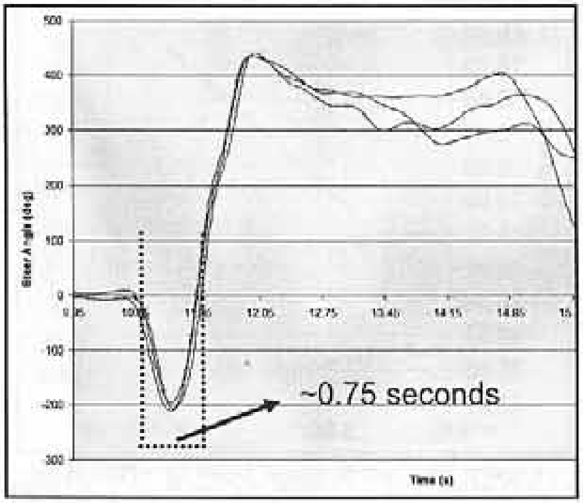



Figure 6: Steer Input for Non-Rollover Runs

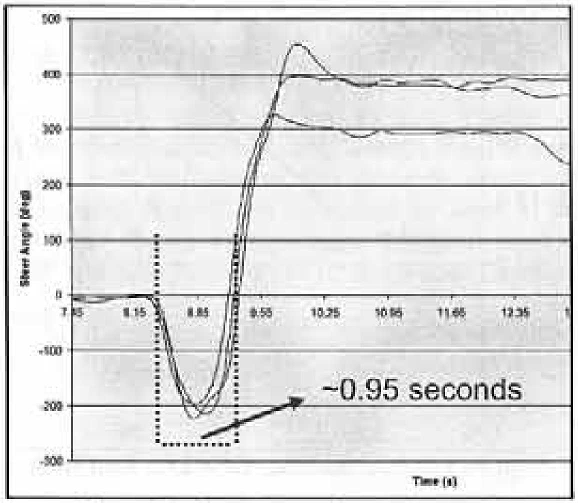



Figure 7: Steer Input for Rollover Runs

Comparison of roll angle data shows a clear difference from the runs where the steering transition was quick. In Figures 8-10, the first roll angle actually has a double peak. The vehicle oscillates due to the first steer input. The second of the two peaks was larger or the same as the first for the three tip-up runs. The delayed steer allowed the vehicle to oscillate and created a much more dangerous condition than the quick transition steer. Review of rollover resistance tests on other vehicles show similar roll behavior to the Explorer, but not all vehicles exhibit this double oscillation behavior.

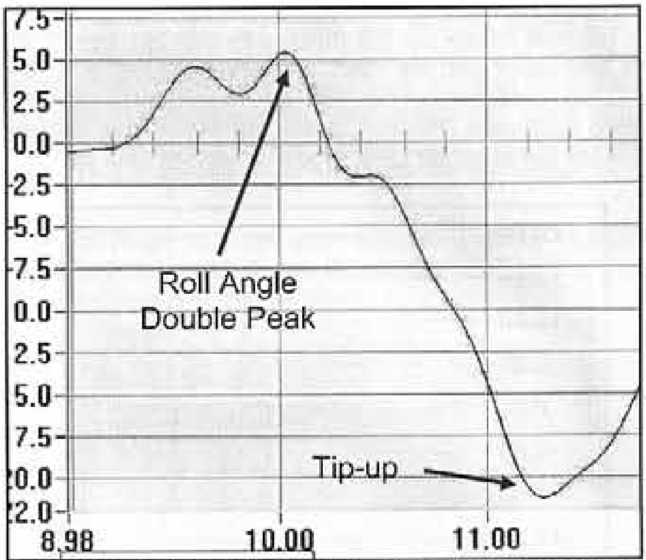



Figure 8: Run Number DSM19 – Roll Angle (54.6 mph)

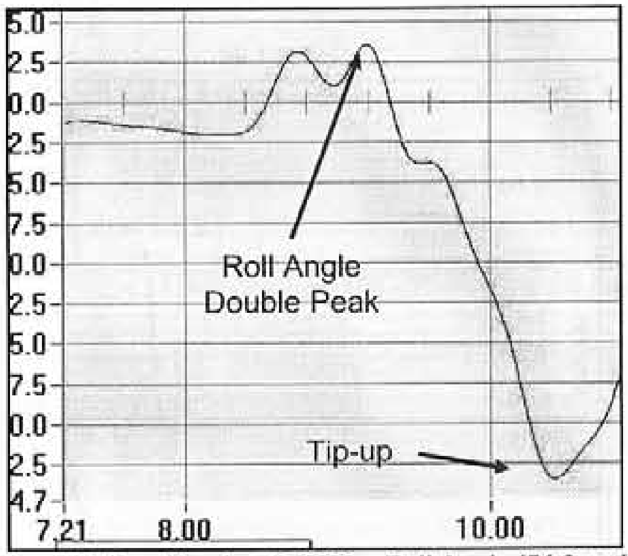



Figure 9: Run Number DSM20 – Roll Angle (54.6 mph)

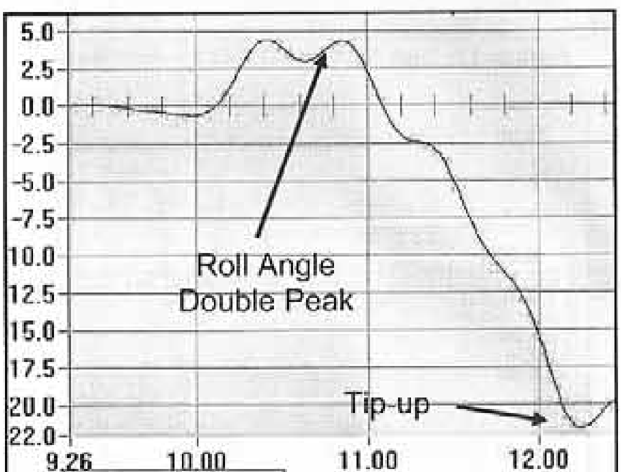



Figure 10: Run Number DSM21 – Roll Angle (54.9 mph)

The roll rate traces for the three human steer non-tip-up runs also show that the steer was reversed just after the first zero crossing of the roll rate trace, preventing a second oscillation (Figures 11-13). In these runs, the roll rate does not even get back to zero a second time.

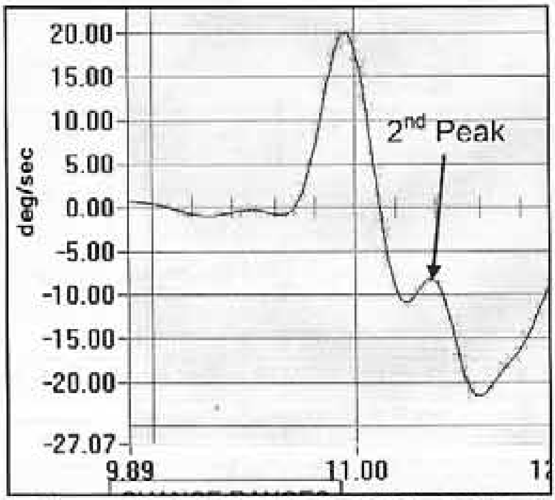



Figure 11: Run Number DSM14 – Roll Rate

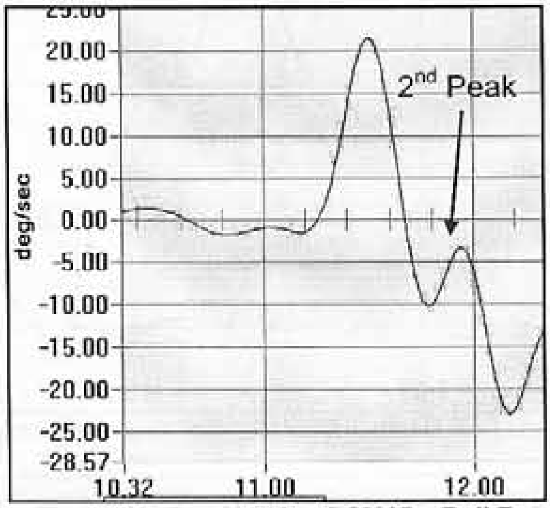



Figure 12: Run Number DSM15 – Roll Rate

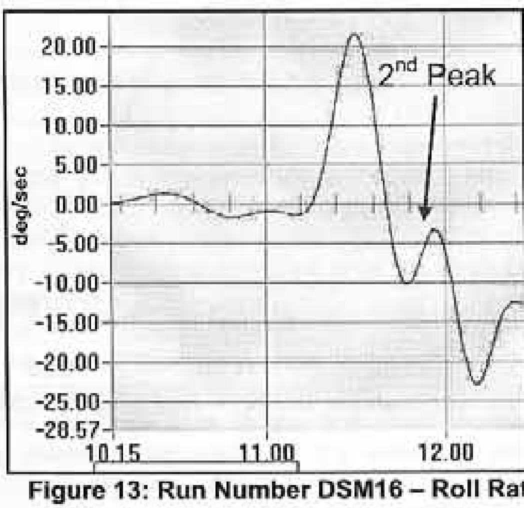



Figure 13: Run Number DSM16 – Roll Rate

The roll rate traces for the three human steer tip-up runs show that the vehicle rocks back and forth two times before the steer is reversed (Figures 14-16). The trace crosses zero two distinct times before the vehicle rolls the other way and ultimately rolls over to outrigger contact.

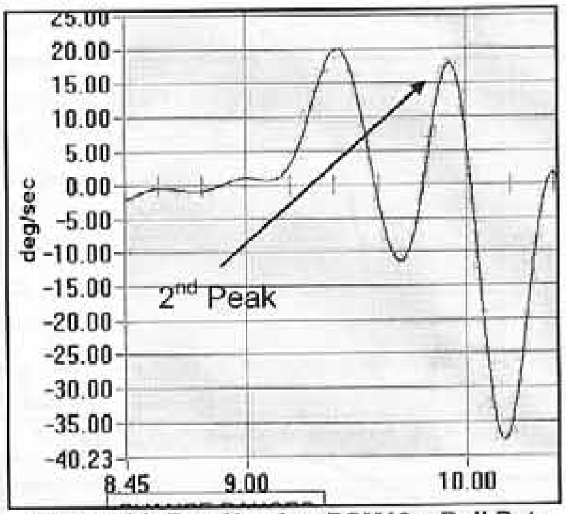



Figure 14: Run Number DSM19 – Roll Rate

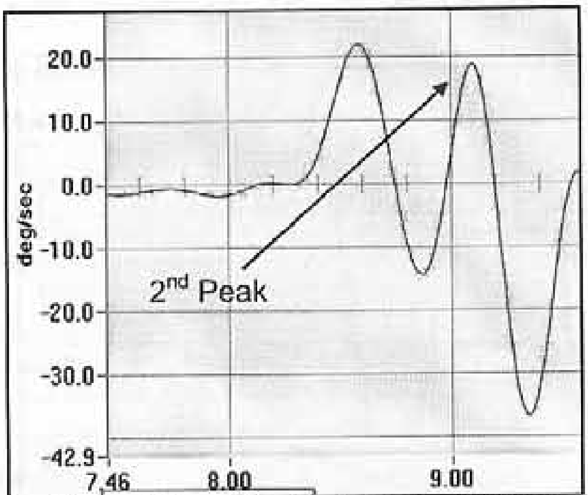



Figure 15: Run Number DSM20 – Roll Rate

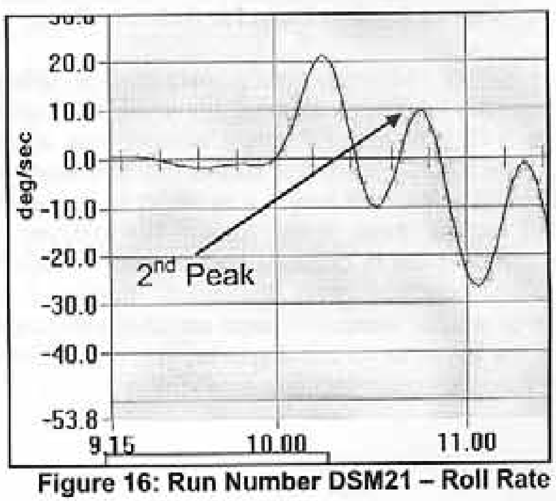



Figure 16: Run Number DSM21 – Roll Rate

Gilbert Engineering has also tested a 1995 Ford Explorer 4-door 4x2. The vehicle's oscillation behavior was nearly identical to the 1997 Explorer 4-door 4x4. The vehicle tipped up at 45.2 mph. Figure 17 shows the double peak roll angle observed during this testing.

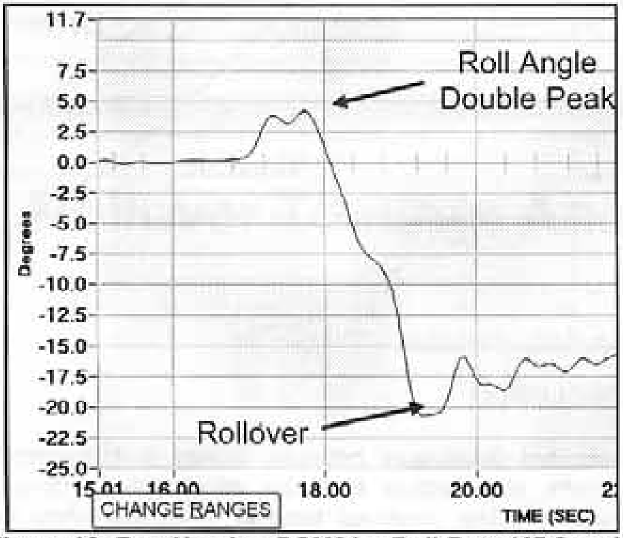



**Figure 16: Run Number DSM21 – Roll Rate (45.2 mph)**

**NHTSA TEST RESULTS**

NHTSA recently tested two Ford Explorer models, a 2001 Ford Explorer 2-door 4x2, and a 2001 Ford Explorer 4-door 4x4, with its fishhook test protocol, which involved different steer magnitudes and rates as seen in the test driver runs. Figure 17 represents the steer input for the NHTSA test runs 100 and 101 on the 2-door Explorer.

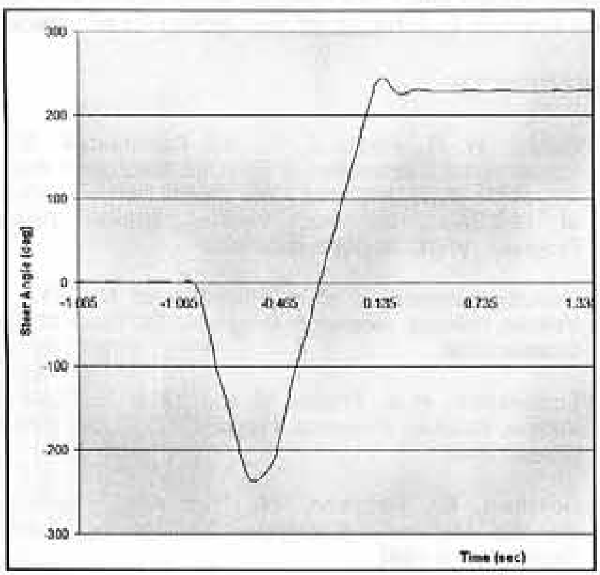



**Figure 17: NHTSA Steer Input for Runs 100, 101**

Review of the data for these two vehicles shows that the steer was reversed at the first zero crossing of the roll rate, which, like in the human steer tests, caused the roll angle to pause before reversing. The vehicle was trying to roll a second time in one direction while being steered the other way. This is similar to the double oscillation observed.

The Roll Angle vs. Time graphs below (Figures 18 and 19) represent the most severe of the test runs on the 2-door Explorer (about 50 mph).

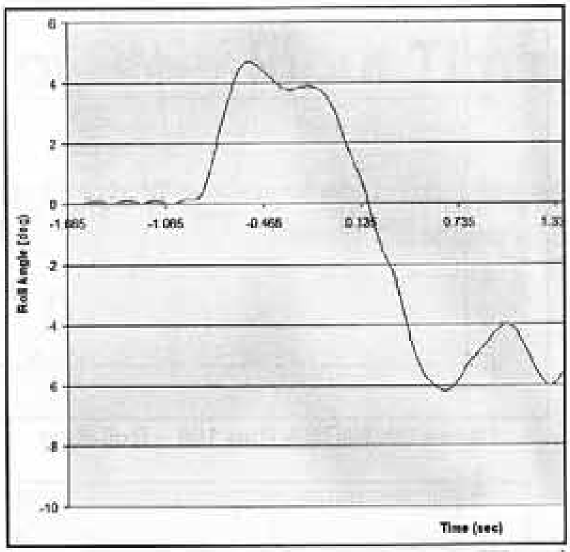



**Figure 18: NHTSA Run 100 – Roll Angle (50 mph)**

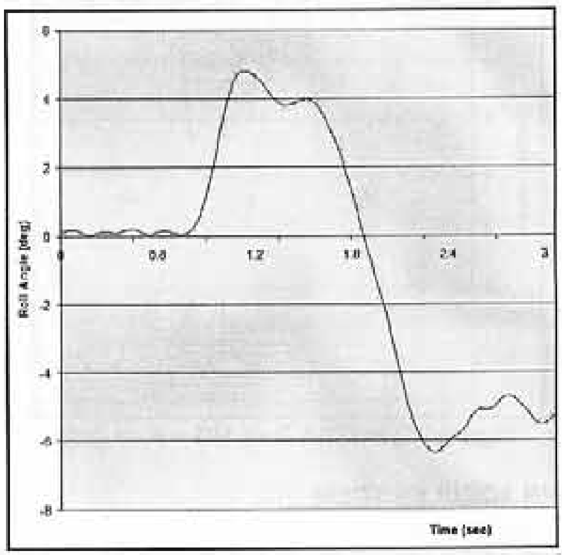



**Figure 19: NHTSA Run 101 – Roll Angle (50 mph)**

Figures 20 and 21 show that for both NHTSA runs, the roll rate crossed zero and the steering was reversed, but the roll rate goes back positive for a short time. This oscillation behavior was the same for both the 2-door and 4-door Explorers tested by NHTSA. Neither of these vehicles tipped up in the NHTSA testing.

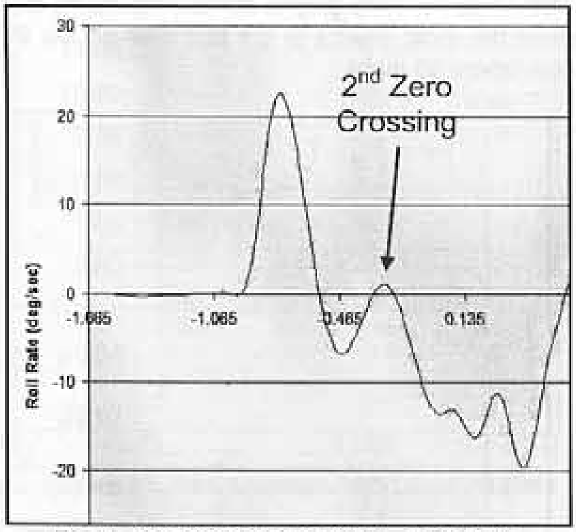



Figure 20: NHTSA Run 100 – Roll Rate

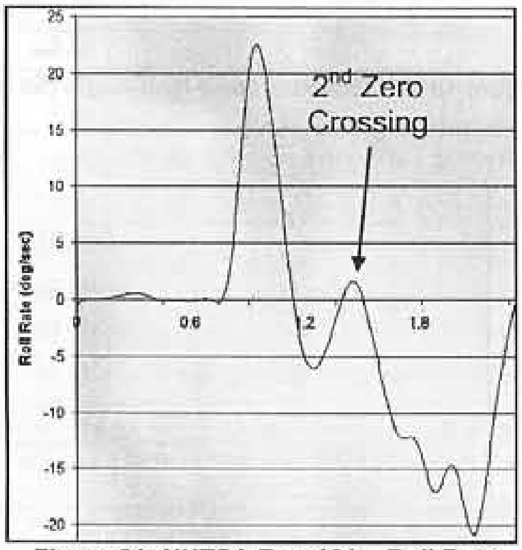
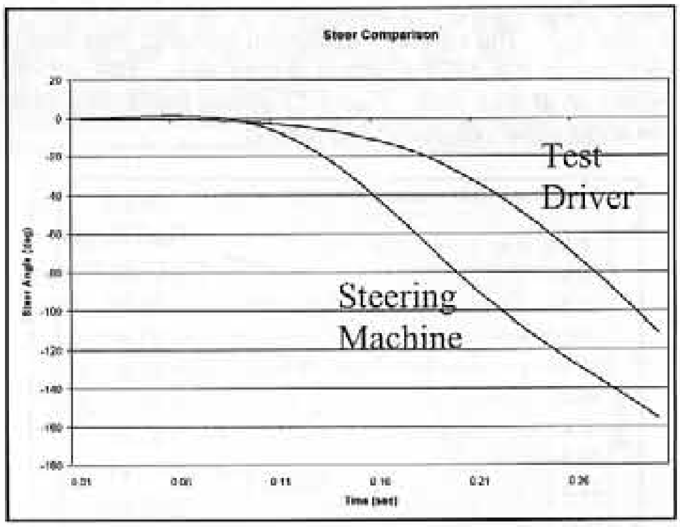



Figure 21: NHTSA Run 101 – Roll Rate

## STEER ACCELERATION

Another noticeable difference between the trapezoidal machine steer and the human steer is the time between zero steer angle and when the steer reaches a linear rate. The seat-of-the-pants feel between the two is different. The vehicle does not react as abruptly to the trapezoidal steer, even though the input is more abrupt.

When closely examining the two steering traces, it is clear that the human steer acceleration to the linear rate takes longer than the trapezoidal input. The trapezoidal machine steer demands the front tires to turn the vehicle faster than a human steer is able to.




## CONCLUSION

There are differences between human and trapezoidal machine steer inputs that can affect vehicle dynamic response. The observed tests in this paper show that some vehicles exhibit a double oscillation in their roll behavior that could have a significant effect as to whether or not tip-up and likely rollover occurs.

Close examination of NHTSA's two-steer tests of Ford Explorers show that the roll rate feedback loop may not accurately predict worst-case scenario. The test driver steer inputs clearly show that a longer delay in steer causes tip-up (untripped rollover) for this vehicle type.

The current NHTSA rollover resistance test program has had a great safety benefit on current SUVs. It is recommended that more work be done to evaluate worst-case scenario to enhance rollover testing for all vehicles.

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[2] Garrott, Forkenbrock, et al, Phase IV of NHTSA's Light Vehicle Rollover Research Program", DOT HS 809 513, October 2002

[3] Forkenbrock, et al, Phases VI and VII of NHTSA's Light Vehicle Rollover Research Program", DOT HS 809 547, October 2003

[4] Heitzman, EJ, Heitzman, EF, "The ATI Programmable Steering Machine", Automotive Testing, Inc. Technical Report, March 1997

[5] Gilbert Engineering LLC Test Procedure, Double Steer Maneuver

[6] Docket No. NHTSA-2001-9663; Notice 3, Rollover Resistance