DYNAMIC ANALYSIS OF SIDE-BY-SIDE UTILITY AND RECREATIONAL VEHICLES

Alex Roberts
The Engineering Institute
USA
Paper Number 09-0260

ABSTRACT

Over the past several years, there has been seen an increasing popularity of side-by-side utility and recreational vehicles (also referred to as UTVs and ROVs), which resemble road-going passenger vehicles more so than typical ATVs due to bench/bucket seats, safety belts, steering wheels, etc. Some of these perceived safety advances over standard ATVs are reasons for their increased popularity. Therefore, it is important to begin using basic passenger car vehicle dynamics knowledge and testing techniques to enhance the safety of these vehicles by making them perform more like road-going vehicles in terms of both directional stability and rollover resistance.

Recent research by The Engineering Institute has resulted in a quantification of the performance aspects of a typical side-by-side using standard automobile tests such as SAE J266, ISO Avoidance Maneuvers, J-turns, and a slalom course. Simple vehicle modifications were also performed that dramatically improved the performance of the vehicle through the same maneuvers.

This paper will discuss the results of both the testing on the standard and modified vehicle. Data from the testing will be presented, and the vehicle modifications will be illustrated. Conclusions will be made detailing the effectiveness of using basic passenger car vehicle dynamics principles at drastically improving the safety of side-by-sides.

INTRODUCTION

Understeer, oversteer, static stability, and dynamic rollover resistance are basic principles of vehicle dynamics understood by engineers with a vehicle dynamics background.

Analysis of a vehicle's understeer or oversteer tendency is a good first approximation of a vehicle's directional controllability. In fact, SAE J266, the standard which describes the test methods for determining and quantifying the understeer or oversteer of a vehicle is entitled *Steady-State Directional Control Test Procedures for Passenger Cars and Light Trucks.* The scope of this document states that, "This SAE Recommended Practice establishes consistent test procedures for determination of steady-state directional control properties for passenger cars and light trucks with single axles." [1]

ISO 4138, *Passenger cars—Steady-state circular driving behavior—Open-loop test methods*, echoes this in its scope by saying, "This International Standard specifies open-loop test methods for determining the steady-state circular driving behaviour of passenger cars…, such behaviour being one of the factors comprising vehicle dynamics and road-holding properties." [2]

The static stability of a vehicle has long been recognized as a good first order approximation, albeit a conservative one, of a vehicle's rollover resistance. The National Highway Traffic Safety Administration (NHTSA) has described it as a "primary means" of determining the risk of rollover [3].

A vehicle's static stability is just that, static. Dynamic rollover resistance addresses the dynamic stability of a vehicle including suspension effects by testing the vehicle through various maneuvers including maneuvers which are considered limit-handling maneuvers.

VEHICLE TESTING

Typical Passenger Cars/Light Trucks

The majority of road-going vehicles exhibit linear-range and limit understeer when tested in accordance with SAE J266. These vehicles usually show a distinct upturn in the understeer gradient, measured by plotting the wheel angle in degrees versus the lateral acceleration corrected for the vehicle roll angle and taking the slope, as the vehicle nears the limits of tire adhesion. If the front tires of the vehicle reach their tractive limits prior to the rear, the vehicle understeers.

Figure 1 shows plots for a typical passenger vehicle which exhibited limit understeer during a clockwise and counterclockwise constant radius, slowly increasing speed test. Note that the slope is positive throughout the range of handling with a distinct increase in its positive slope up to the point that the tires have saturated, and the test driver is no longer able to keep the vehicle on path, the termination condition for the test.

For the tests plotted below, the vehicle was tested on an approximately 40 m radius circle.

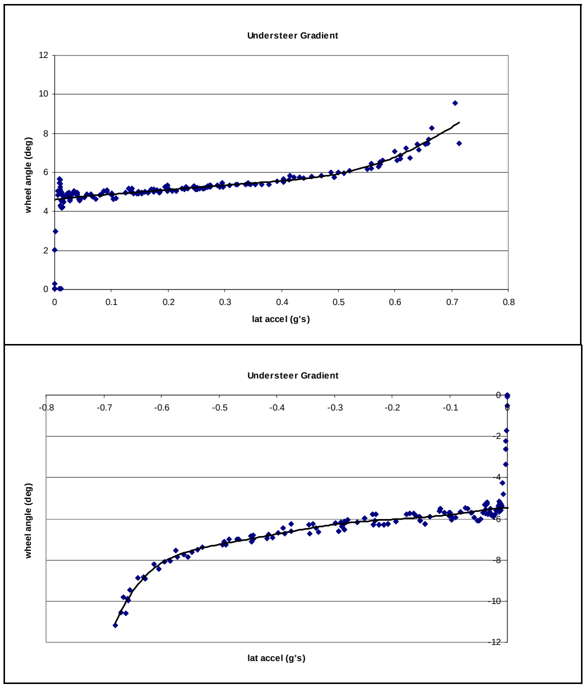


Figure 1. Understeer gradient plots for a typical passenger vehicle.

NHTSA has published data concerning the static stability in the form of the static stability factor.

$$SSF = \frac{1}{2}\frac{Trackwidth}{CG\ Height} \quad (1)$$

NHTSA's data shows a range from 0.95 for the 1992-2000 Mitsubishi Montero 4dr, 4X4 to nearly 1.8 for the previous generation Corvette.

With regards to dynamic rollover resistance, some road-going vehicles have been made to tip in limit-handling maneuvers at high lateral accelerations (0.8 g's +).

Side-by-Side Recreational Vehicle

Static Analysis-A side-by-side recreational vehicle was tested by The Engineering Institute.

Firstly, the vehicle was tested in order to determine its static stability factor, as a means of determining how it compared to the road-going vehicles previously tested by NHTSA. The center of gravity height of the vehicle was determined by locking the suspension and placing the vehicle on a tilt-table.

The protocol used was as follows:

- Document the vehicle "as received."
- Determine loading configurations to be tested.
- Place dummies and cargo (if applicable) in the vehicle to simulate the loading configurations.
- Measure shock/spring or strut/spring length at ride height for each loading configuration.
- Measure the track width for each.
- Fabricate adjustable suspension rods to fix the ride height at the measured values.
- Load the vehicle to the desired loading configuration and set the suspension rod to the corresponding length.
- Place the vehicle on the tilt table with the leading tires on the high friction surface and their edges against the wooden 11/16" high curb.
- Tether the trailing edge of the vehicle to the table so that the trailing tires can lift from the platform, but do not allow the vehicle to tip all the way over.
- Raise one side of the platform until both of the trailing tires lift from the platform.
- Document the angle at which this lift occurred.
- Perform at least two tests passenger side leading and two tests driver's side leading.
- If data is not consistent, perform additional tests.

The test vehicle was tested in four configurations. These were vehicle only, vehicle plus 73 kg water dummy in the driver's seat, vehicle plus 73 kg water dummies in both the driver's and passenger's seat, and vehicle plus two 73 kg water dummies and cargo placed in the bed up to GVWR.

The results of the static testing are summarized in Table 1.

Table 1.
SSF test results.

Configuration	Avg CG Height (mm)	Average SSF
Vehicle Only	622	0.88
Vehicle Plus 73 kg Driver	693	0.79
Vehicle Plus 73 kg Driver and Passenger	719	0.77
GVWR	790	0.71

Two things of note from the above table are that (1) the unloaded SSF of this vehicle is lower than that of any road-going vehicle as reported by NHTSA, and (2) the low curb weight of this type of vehicle results in passenger loading having a large effect on the static stability of the vehicle.

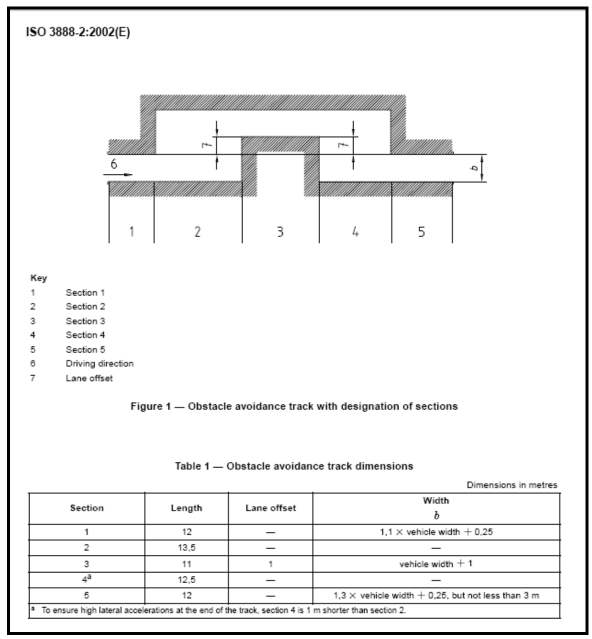
Dynamic Analysis-A vehicle whose static stability predicts tip-up at acceleration levels of less than 0.9 g's has a high risk of a rollover on a flat, level surface. In order to assess this, dynamic testing was carried out on the vehicle. The photograph below shows the vehicle prepared for dynamic testing.

Figure 2. Test vehicle as prepared for testing (Yamaha Rhino 450).

To determine understeer/oversteer characteristics SAE J266: *Steady State Directional Control Test Procedures for Passenger Cars and Light Trucks* [1] constant radius, slowly increasing speed circle test was used as a test basis. These tests were conducted in both the clockwise and counterclockwise directions. *J266* recommends a minimum radius of approximately 30.5 m. However, due to the lower top-end speed of these vehicles, this radius was reduced to 15.25 m for this testing, resulting in a 30.5 m diameter circle. This diameter is in agreement with the Consumer Product Safety Commission's recommended use of a 30.5 m diameter circle test for ATV analysis to determine both the "maximum dynamic lateral acceleration in a turn" and the vehicle's understeer and oversteer characteristics in their *All Terrain Vehicles (ATVs) Project Status Report, February, 2008* [4].

Though the steady state circle test is a good indicator of the amount of understeer designed into the vehicle, it is not very representative of any real world dynamic driving maneuvers. Therefore, dynamic maneuvers were also performed to evaluate the transient dynamics of the vehicle. The purpose was to subject the vehicle to maneuvers to evaluate the non steady-state handling characteristics of the vehicle. The standard maneuvers chosen were avoidance maneuvers, step-steers, and slalom courses. A non-standard maneuver which was also evaluated was a U-turn from a stop or from a slow rolling speed.

The vehicle was driven at various speeds through an accident avoidance maneuver. The avoidance maneuver was patterned after the ISO International Standard 3888-2 *Passenger cars — Test track for a severe lane-change manoeuvre —Part 2: Obstacle avoidance* [5]. The width measurements for this course are based on vehicle width. Figure 3 shows the track and dimensions. As shown in the figure, the driver operates the vehicle through Section 1 in the direction marked by the number 6. As the driver enters Section 2, he/she steers left then right to enter the offset Section 3 (i.e. avoid an obstacle in the path of Section 1). At the end of Section 3 as the vehicle is entering Section 4, the driver steers right then left to enter Section 5.


ISO 3888-2:2002(E)

Key
1 Section 1
2 Section 2
3 Section 3
4 Section 4
5 Section 5
6 Driving direction
7 Lane offset

Figure 1 — Obstacle avoidance track with designation of sections

Table 1 — Obstacle avoidance track dimensions

Dimensions in metres

Section	Length	Lane offset	Width b
1	12	—	1,1 × vehicle width + 0,25
2	13,5	—	—
3	11	1	vehicle width + 1
4[a]	12,5	—	—
5	12	—	1,3 × vehicle width + 0,25, but not less than 3 m

[a] To ensure high lateral accelerations at the end of the track, section 4 is 1 m shorter than section 2.

Figure 3. ISO avoidance maneuver illustration and dimensions. [5]

The ISO standard calls for the vehicle throttle (gas pedal) to be released at the entrance speed at the timing strip. Due to the large amount of drag and engine braking with this vehicle, at the timing strip, the vehicle was shifted into neutral as the throttle was released. After the throttle release, the driver steers left then right to enter the offset lane. At the end of the offset lane, the driver steers right then left to reenter the last lane. The standard states: *The obstacle avoidance manoeuvre is a dynamic process which involves rapidly driving a vehicle from its initial lane to another lane parallel to the first, and returning to the initial lane, without exceeding lane boundaries. The objective is to have the vehicle reach a certain sequence of alternate high, lateral accelerations such that the vehicle's lateral dynamics can be evaluated.*

A second maneuver used was a step steer maneuver with various speeds. During this maneuver the driver reached the target speed and rapidly applied the predetermined steering angle and then held the steering and throttle constant. 180 degree and 270 degree target step steers were conducted at various speeds. The step steer test is patterned after ISO 7401, *Road vehicles — Lateral transient response test methods — Open-loop test methods* [6].

A third maneuver was based on the slalom maneuver used by Chrysler. Due to the relatively low top speed of this vehicle, the spacing between cones in the slalom was set to 15.25 m.

A non-standard maneuver used for vehicle evaluation was a U-turn accelerating from a stop and from low speeds. During this maneuver, the driver accelerated while turning the steering wheel sharply to complete a U-turn.

The testing was conducted on flat, level concrete for repeatability and comparison purposes as well as a grass surface.

<u>Circle Testing Analysis</u>-During the circle testing, the side-by-side exhibited both understeer and a transition to oversteer. This transition placed a high burden on the driver, as constant corrective steering in the form of a reduction in the steering angle was necessary to keep the vehicle on path. The vehicle would suddenly lose rear grip at which time the yaw rate would quickly increase (see Figure 4) and the driver would have to arrest this with counter-steer. This made the vehicle highly unpredictable. Test video shows the driver constantly sawing the steering wheel to remain on radius.

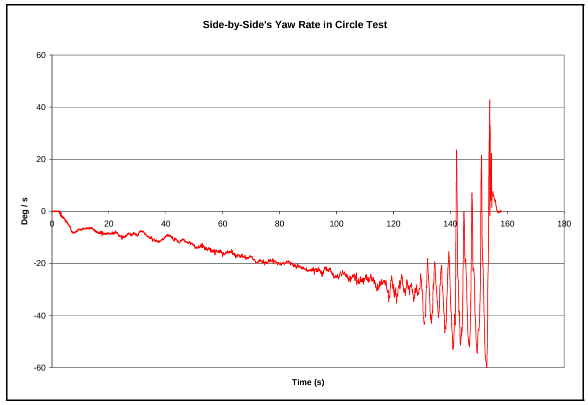


Figure 4. Yaw rates from circle test.

After the test data was processed, understeer plots were generated. These plots clearly show just how unpredictable and directionally unstable the vehicle is. The plots also indicate that the vehicle is beginning the transition to an oversteer vehicle at very low lateral accelerations of 0.25 g's, a value that is typically still considered the steady-state range of vehicle operation.

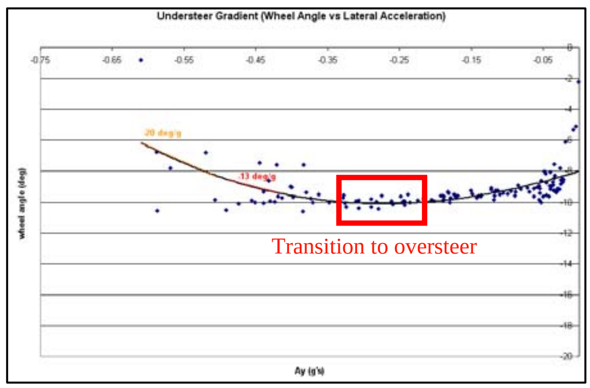


Figure 5. Understeer gradient plot showing transition to oversteer at 0.25 g's and terminal oversteer.

Not only did the vehicle exhibit directional instability in the circle testing, the vehicle even tipped onto the outriggers during the circle testing. As seen from the above plot, the maximum lateral acceleration attained in the testing was less than 0.65 g's.

<u>Obstacle Avoidance Testing Analysis</u>-The avoidance maneuver showed similar results to those seen in the circle testing. The vehicle exhibited a sudden loss of grip at the rear (indicated on the plots by the high yaw rates as shown in Figure 6 for example) and if this was not arrested, the vehicle tipped. The tips in the avoidance maneuver occurred at a similar lateral acceleration as in the circle test with a value of 0.67 g's.

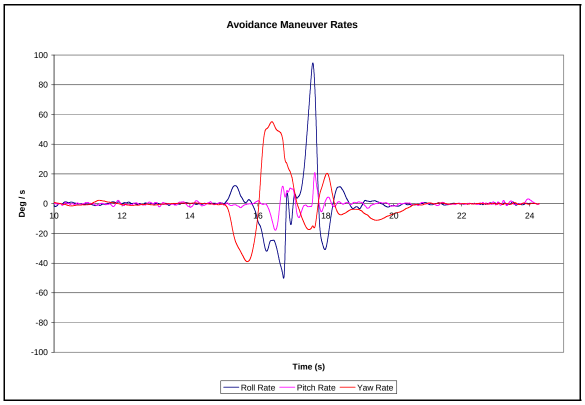


Figure 6. Plot of rates (yaw rate in red) from an avoidance maneuver that resulted in rollover.

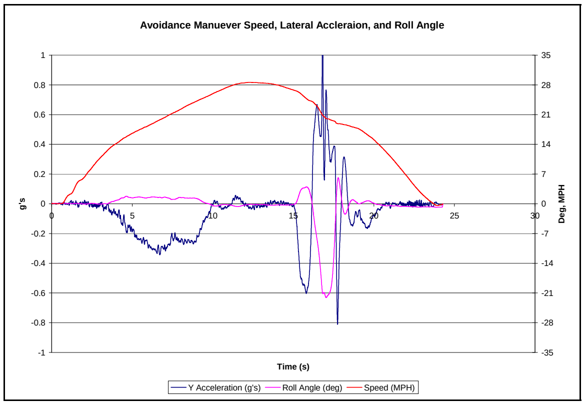


Figure 7. Avoidance maneuver plot showing speed, lateral acceleration, and roll angle.

Step-Steer Testing Analysis-The step-steers resulted in tip-ups at the lowest lateral accelerations of any of the tests. Tip-up occurred in 8 of the 18 step steer tests performed on the first day of testing with lateral accelerations as low as 0.55 g's, an extremely low lateral acceleration to cause tip-up.

Figure 8 shows this. Note that the speed at tip is around 14 mph (22.5 kph).

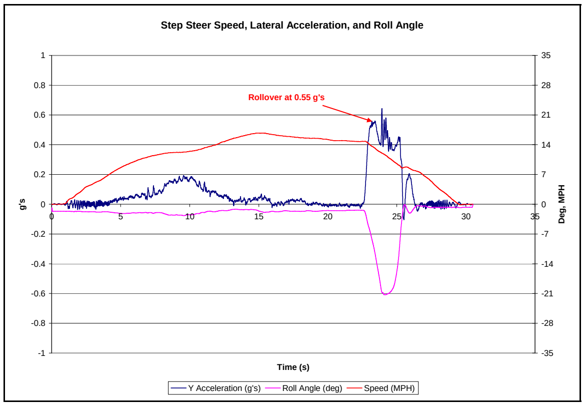


Figure 8. Step steer test data.

Slalom Testing Analysis-During the slalom test, the dynamics echoed those from the circle and avoidance maneuvers. The vehicle exhibited oversteer during the mauever, and could be made to drift around the cones. Tip occurred in these tests at 0.57 g's.

U-Turn While Accelerating Testing Analysis-During this type of test, the vehicle tipped onto the outriggers at a lower speed than in any other tests, approximately 19 kph (12 mph). Tip occurred consistently in the lateral acceleration range of 0.57 to 0.63 g's.

General Analysis of Dynamic Testing-The dynamic testing revealed a two-part instability with the vehicle. The vehicle consistently showed a loss of directional stability due to a loss of grip at the rear tires sometimes followed by a tip-up of the vehicle onto two wheels or completely onto the outriggers.

Figure 9. Frame capture from vehicle testing showing onset of loss of directional stability characterized by a lifting of the inside rear tire (the green is speed in mph).

As was felt by the test driver, and is easily seen during the maneuvers and in Figure 9, the loss of rear grip is instigated by a lifting of the inside rear wheel during a turning maneuver. This indicates that the rear of the vehicle is too stiff in relation to the front. The 2000 Edition of the SAE *Manual on Design and Manufacture of Torsion Bar Springs and Stabilizer Bars* [7] warns against a rear-only stabilizer bar. The manual states that, "Stabilizer bars are generally installed on both front and rear suspensions or in front suspension only. Use of a stabilizer bar on the rear suspension only can sometimes have an adverse effect on vehicle handling. Such installations should be tested under severe cornering conditions to ensure the desired handling characteristics."

The use of the anti-sway bar on the rear of the vehicle is mandated by the rear-drive. The rear drive of the test vehicle does not employ a differential, rather the axle shafts are splined and both shafts are driven at the same angular speed. This configuration would result in heavy tire scrub and understeer while cornering if not for the anti-sway bar being used to unweight and lift the inside tire. This lifting of the inside rear wheel is highly derogatory to the vehicle handling.

Appendix A is a summary table of the first set of the standard vehicle testing.

Vehicle Modifications-The vehicle was modified with a two-fold purpose. The goals were (1) to increase the directional stability and (2) to increase the rollover resistance. A secondary aim was to achieve these goals with as simple vehicle modifications as possible.

Simple vehicle dynamics principles were employed to accomplish these goals. In order to increase the directional stability, it was known that the roll stiffness balance needed to be altered to reduce that of the rear of the vehicle in relation to the front. To accomplish this, it was decided that the rear anti-sway bar must be removed. As discussed earlier, severe tire scrub and understeer would result if this was the only modification made. Therefore, a modification to the rear-drive had to be made as well. The test vehicle is a four-wheel-drive model which employs a front differential. The front differential was taken from another vehicle and mounted on the rear of the test vehicle.

In order to increase the rollover resistance, there were two basic options as evident from Equation 1. The center of gravity height could be lowered or the trackwidth could be widened. The second option was easy to perform as aluminum wheel spacers are currently on the market for this type of vehicle. In fact, the website from which the spacers were ordered advertised them as increasing the cornering stability. The spacers are approximately 5 cm wide. Two spacers were added at each corner giving a little over 20 cm increase of the front and rear trackwidth. The modifications are shown below.

Figure 10. Modifications to the test vehicle.

Modified Vehicle Dynamic Testing Analysis-The vehicle modifications drastically improved the vehicle stability. The vehicle was much more directionally stable and predictable. The rollover resistance was also greatly improved.

The modified vehicle performed dramatically better in the circle testing. The vehicle exhibited linear range understeer with the understeer increasing until the test was terminated with limit understeer in both directions. The vehicle did not tip onto the outriggers in either test.

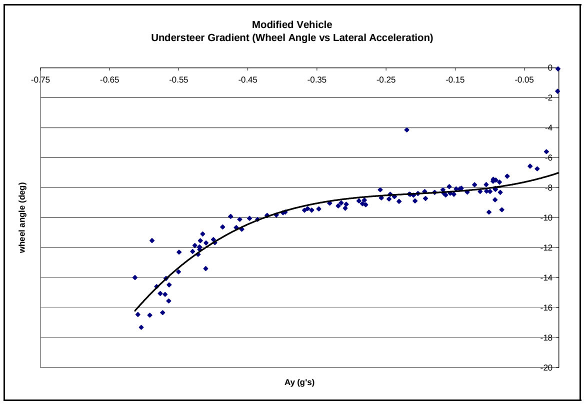


Figure 11. Circle test data plot for the modified vehicle.

The alternative design performed significantly better in the 15.25 m slalom testing. The vehicle had successful runs through the course with recorded lateral accelerations of 0.43, 0.64, and 0.83 g's with no tips onto the outriggers. During the slalom, the standard vehicle rolled over at 0.57 and 0.62 g's. The alternative design required 0.85 g's to rollover. The alternative design rolled over on the fourth steer after the roll momentum had built up throughout the maneuver. 0.85 g's is a 49% increase over 0.57 and is a 37% increase over 0.62 g's. Further tuning of the suspension system through spring rate modifications would likely eliminate rollover.

The alternative design did not roll over in any of the 180 degree left step steers even with lateral accelerations as high as 0.87 g's with a corresponding entrance speed of 51.5 kph. The standard design did rollover at 0.68 g's in the 180 degree left step steer. The alternative design did roll over onto the outriggers at 0.88 g's in the 270 degree left step steer with and entrance speed of 29 mph. The standard configuration rolled over at only 16 mph with a lateral acceleration of 0.68 g's. A 0.88 g rollover threshold equates to a 29% increase over 0.68 g's.

The alternative design did not roll at all in any of the four U-turn tests; whereas, the standard design rolled over in 11 out of 12 tests with speeds of approximately 19 kph at the time of rollover.

Appendix A shows a summary of the modified testing.

CONCLUSIONS

The following conclusions were made based on the dynamic testing of the side-by-side vehicle.

Testing revealed the standard configuration side-by-side is directionally unstable characterized by a transition to severe oversteer at lateral accelerations as low as 0.25 to 0.3 g's.

A variety of test maneuvers on concrete and on grass demonstrated that this vehicle will roll over from driver steering inputs at low lateral acceleration levels. Testing demonstrated rollovers at lateral accelerations as low as 0.55 g's. This rollover threshold is very low and can easily be exceeded even during proper use of the vehicle.

Testing of the alternative design showed that simple design changes greatly increased the directional stability. The alternative design showed a drastic improvement in the rollover threshold of this vehicle as well with lateral accelerations as high as 0.87 g's on concrete not resulting in rollover.

REFERENCES

1. SAE J266, *Steady-State Directional Control Test Procedures for Passenger Cars and Light Trucks*, Society of Automotive Engineers, 1996.
2. ISO 4138:2004, *Passenger cars—Steady-state circular driving behavior—Open-loop test methods*, Third edition 2004-09-15, International Organization for Standardization, 2004.
3. Walz, M.C., DOT HS 809 868 *Trends in the Static Stability Factor of Passenger Cars, Light Trucks, and Vans*, NHTSA, 2005.
4. Consumer Product Safety Commission, *All-Terrain Vehicles (ATVs) Project Status Report*, February, 2008.
5. ISO 3888-2:2002, *Passenger cars—Test track for a severe lane-change manoeuvre—Part 2: Obstacle avoidance*, First edition 2002-11-15, International Organization for Standardization, 2002.
6. ISO 7401:2003, *Road vehicles—Lateral transient response test methods—Open-loop test methods*, Second edition 2003-02-15, International Organization for Standardization, 2003.
7. *SAE Manual on Design and Manufacture of Torsion Bar Springs and Stabilizer Bars, 2000 Edition, HS-796*, Society of Automotive Engineers, 2000 revision.

Appendix A: Summary Table of Standard and Modified Vehicle Testing

Table 2.
Summary of standard configuration testing.

Test #	Test Type	Target Speed (mph)	Actual Speed (mph)	Tip?	Approx Lat Accel at Tip (g's)	Max Lat Accel for Manuever with No Tip (g's)	Notes
1	Circle, CCW	N/A	N/A	Y	0.74		
2	Circle, CW	N/A	N/A	N			Data acquisition error
3	50 ft. Slalom	15		N			Data acquisition error
4	50 ft. Slalom	20		N			Data acquisition error
5	50 ft. Slalom	25					System power off, run aborted
6	50 ft. Slalom	25	25	N		0.7	
7	50 ft. Slalom	25	25.5	Y	0.57		
8	ISO Avoidance	20	20	N		0.31	
9	ISO Avoidance	25	25	N		0.54	
10	ISO Avoidance	30	29	N		0.48	
11	ISO Avoidance	30	30	Y	0.67		
12	ISO Avoidance	28	27	Y	0.67		
13	ISO Avoidance	26	26			0.61	
14	180 deg Left Step Steer	15	13.5	N		0.49	Steer stop moved, exceeded 180 deg
15	180 deg Left Step Steer	15	14.5	N		0.45	
16	180 deg Left Step Steer	18	18.5	N		0.67	
17	180 deg Left Step Steer	20	20.5	Y	0.68		
18	180 deg Left Step Steer	19	19	N		0.67	
19	180 deg Left Step Steer	20	20.5	Y	0.68		
20	270 deg Left Step Steer	15	16	Y	0.68		
21	270 deg Left Step Steer	15	15	N		0.66	
22	270 deg Left Step Steer	14	14	N		0.66	On-board camera failed during test
23	270 deg Left Step Steer	17					On-board camera failed, run aborted
24	270 deg Left Step Steer	17	16.5	Y	0.66		
25	180 deg Right Step Steer	15	14	N		0.47	
26	180 deg Right Step Steer	17	16.5	N		0.56	
27	180 deg Right Step Steer	18	18	Y	0.58		
28	180 deg Right Step Steer	18	18	Y	0.57		
29	270 deg Right Step Steer	15	15	Y	0.55		
30	270 deg Right Step Steer	14	14	Y	0.56		
31	270 deg Right Step Steer	12	12	N		0.52	
32	U-Turn	N/A	N/A	Y	0.6		Steer sensor out of range
33	U-Turn	N/A	N/A	Y	0.61		Steer sensor out of range
34	U-Turn	N/A	N/A	Y	0.6		
35	U-Turn	N/A	N/A	Y	0.6		Steer sensor out of range
36	U-Turn	N/A	N/A	N		0.6	Steer sensor out of range
37	U-Turn	N/A	N/A	Y	0.57		
38	U-Turn	N/A	N/A	Y	0.63		
39	U-Turn	N/A	N/A	Y	0.59		
40	U-Turn	N/A	N/A	Y	0.6		Steer sensor out of range

Table 3.
Summary of modified configuration testing.

Test #	Test Type	Target Speed (mph)	Actual Speed (mph)	Tip?	Approx Lat Accel at Tip (g's)	Max Lat Accel for Manuever with No Tip (g's)	Notes
1	Circle, CCW	N/A	N/A	N		0.66	
2	Cicle, CW	N/A	N/A	N		0.63	
3	50 ft. Slalom	20	19	N		0.43	
4	50 ft. Slalom	25	26	N		0.64	
5	50 ft. Slalom	30	30	N		0.83	
6	50 ft. Slalom	30	32	Y	0.85		
7	180 deg Left Step Steer	20	21	N		0.7	
8	180 deg Left Step Steer	25	26	N		0.81	
9	180 deg Left Step Steer	30	31	N		0.87	
10	270 deg Left Step Steer	20	20	N		0.79	
11	270 deg Left Step Steer	25	25	N		0.85	
12	270 deg Left Step Steer	30	29	Y	0.88		
13	U-Turn	N/A	N/A	N		0.61	Steer sensor out of range
14	U-Turn	N/A	N/A	N		0.58	Steer sensor out of range
15	U-Turn	N/A	N/A	N		0.62	
16	U-Turn	N/A	N/A	N		0.62	Steer sensor out of range