LOG OF MEETING
DIRECTORATE FOR ENGINEERING SCIENCES

SUBJECT: Recreational Off-Highway Vehicles (ROVs) – Meeting requested by Polaris Industries Inc. (Polaris) to discuss dynamic stability and handling testing and metrics for ROVs.

DATE OF MEETING: March 10, 2015

PLACE OF MEETING: CPSC National Product Testing and Evaluation Center, 5 Research Place, Rockville ,MD.

LOG ENTRY SOURCE: Caroleene Paul, ESME

COMMISSION ATTENDEES: See attached attendance list

NON-COMMISSION ATTENDEES: See attached attendance list

SUMMARY OF MEETING:

Representatives from Polaris met with CPSC staff to discuss testing done by Polaris in the areas of dynamic stability and handling of ROVs.

CPSC staff opened the meeting by reviewing the scope and ground rules for the public meeting:

- The meeting was requested by Polaris to present information on dynamic stability and handling of ROVs.
- Members of the public were reminded of their role as observers and not participants of the meeting.
- The discussion and presentations during the meeting will be treated as comments to the ongoing rulemaking and will become a part of the public record.

Mr. Paul Vitrano, Mr. David Longren, Mr. Louis Brady, and Mr. Damian Harty of Polaris Industries Inc. presented information on dynamic tests that Polaris had performed on ROVs (presentation attached).

Polaris staff presented the following points:

- Divergent instability is “bad” because it increases tripped rollover risk.
- Lateral acceleration is very noisy and polynomial fits are arbitrary.
- Yaw rate measured during a fixed steer test is a cleaner signal and can be used to detect divergent instability.
- J-turn test results on pavement, sand, and gravel surfaces show that understeer ROVs roll over earlier than oversteer ROVs on off-road terrain, and sliding occurred below 0.3 g lateral acceleration and resulted in tripped rollovers that ranged from 0.87 g to 1.1 g (compared to untripped rollover on pavement at 0.72 g).

CPSC staff and Polaris staff discussed lateral acceleration measurement, the relationship of lateral acceleration to yaw rate, and the relationship of static stability to vehicle rollover.

MEETING ATTENDANCE RECORD
Polaris / CPSC Staff – March 10, 2015

COMMISSION ATTENDEES:

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A Handling Quality Metric

Handling Metric Context

A Given: Instability is A Bad Thing

Instability implies response is unbounded with time; in vehicle control terms, an uncommanded spin

Spins not preferred because they may lead to tripped rollover by presenting the vehicle sideways to obstacles/terrain

Four states possible for systems generally[1,2]:

- Asymptotic Stability
- Neutral Stability
- Divergent Instability
- Oscillatory Instability

[1] Fundamentals of Vehicle Dynamics, Gillespie, p402

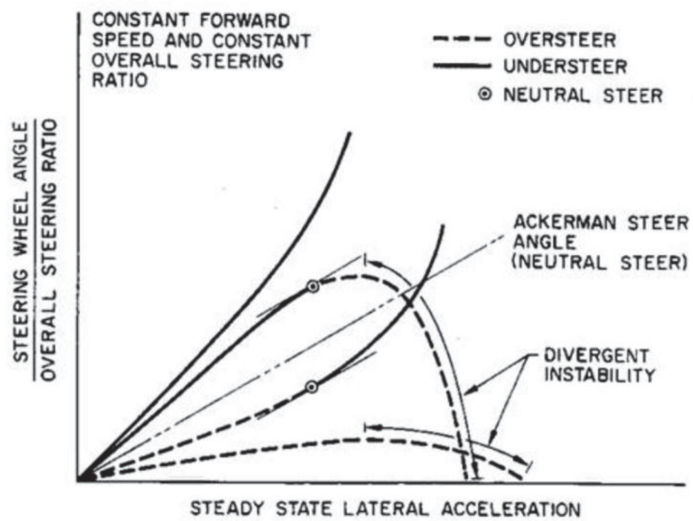
[2] The Multibody Systems Approach to Vehicle Dynamics, Blundell & Harty, p172

[3] Race Car Vehicle Dynamics, Milliken & Milliken, p245

Understeer/Oversteer and Stability

SAE Understeer guarantees oscillatory asymptotic stability in absence of driver input[3]

SAE Oversteer does not predict instability (below)



From Fundamentals of Vehicle Dynamics, Gillespie, p403

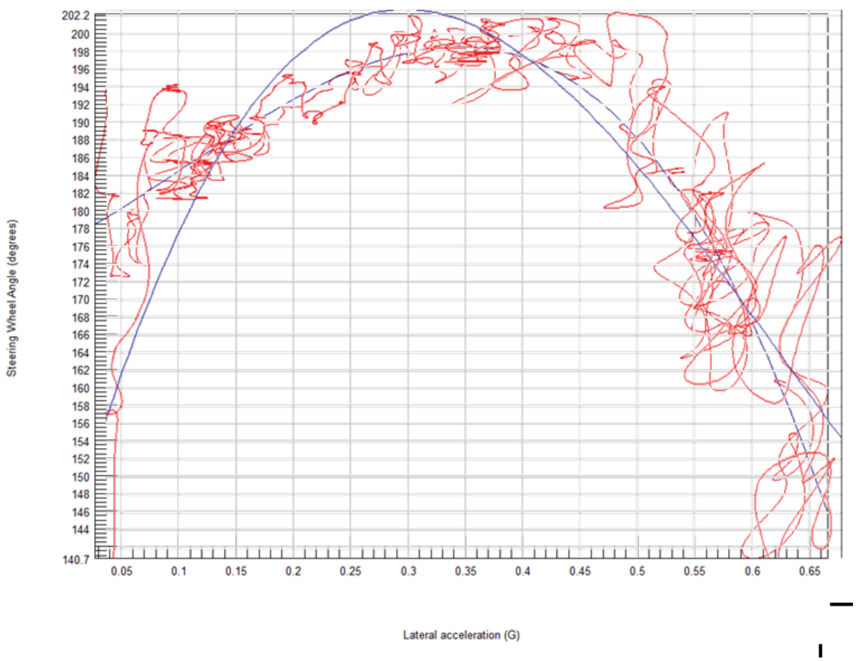
Divergent Instability Better Surrogate for Tripped Rollover Risk

POLARIS

Measurement Noise

Lateral Acceleration Very Noisy

Measurement noise very high on lugged tires with non-deformable terrain



Polynomial Fit Arbitrary

Vehicle motion is the combination of tire forces divided by reluctance of vehicle to move (mass, inertia)[4]

Tires are often represented with so-called "Magic Formula"[5]:

$$Y(X) = D\sin\left[C\arctan\left\{Bx - E\left(Bx - \arctan[Bx]\right)\right\}\right]$$

There is no good reason to fit a polynomial to the data

[4] Newton's 2nd Law

[5] Tyre Modelling for Use in Vehicle Dynamics Studies, SAE 870421, Bakker, Nyborg, Pacejka

Discerning Turning Point Unsatisfactory Experimentally

Another Possible Test Protocol

The Fixed Steer Test

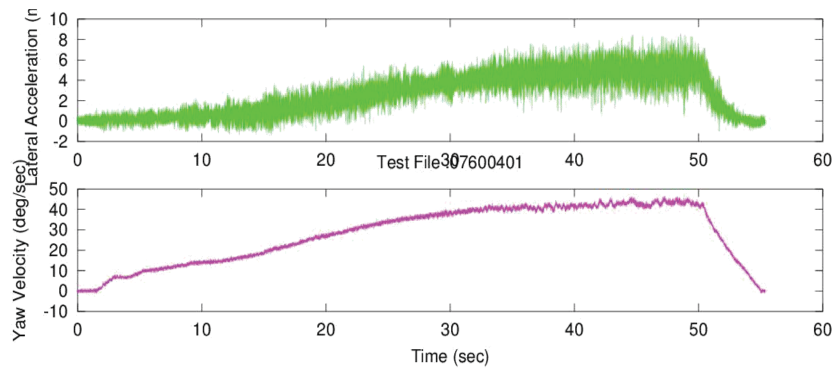
Extremely repeatable and requires no special facilities other than a consistent surface

Unlike constant radius test, it is not a test of the steering robot quality, driver skill, etc

While not directly comparable to other tests (none are directly comparable with each other), will nevertheless expose a vehicle that seeks to spin ("divergent")

Yaw Rate Gives Clean Signal

Yaw rate is rotation viewed in plan



Data not so susceptible to vibration (magenta) when compared to lateral acceleration (green)

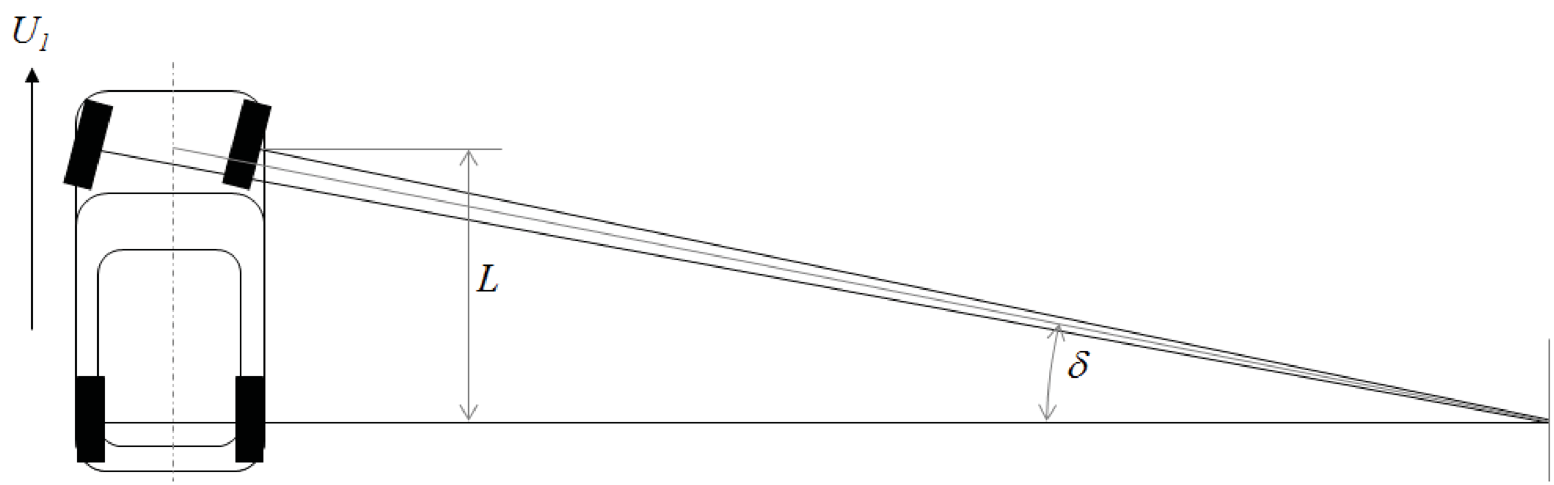
Mount location insensitive (identical readings anywhere on vehicle)

Fixed Steer is Repeatable, Driver-Independent and gives Clean Data

A Geometric Connection

"Non Spin" (aka No-Slip, Steady State) Yaw rate connects to Lateral Acceleration simply: $A_Y = rU$

A "geometric" vehicle will have a yaw rate $r = \frac{U\delta}{L}$ which is identical to a neutral steer vehicle[3]



[3] Race Car Vehicle Dynamics, Milliken & Milliken, p159

Yaw Rate is Directly Connected to Lateral Acceleration

Detecting Divergence – Fixed Steer Results

No Spin Condition

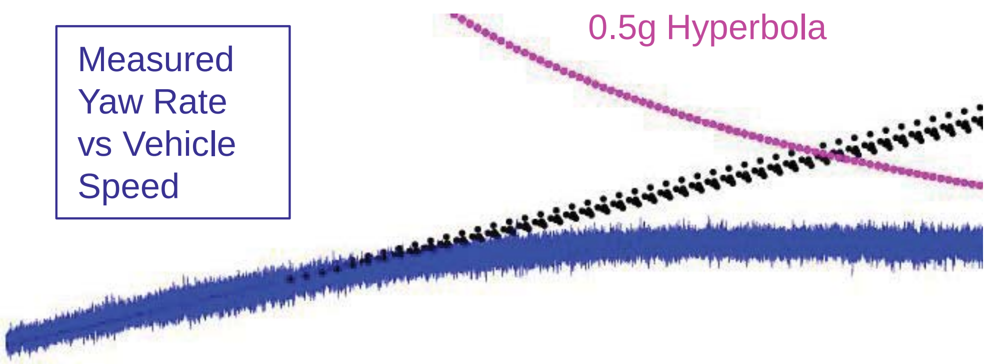
Plotting yaw rate against vehicle speed will show its character compared to a “geometric” vehicle

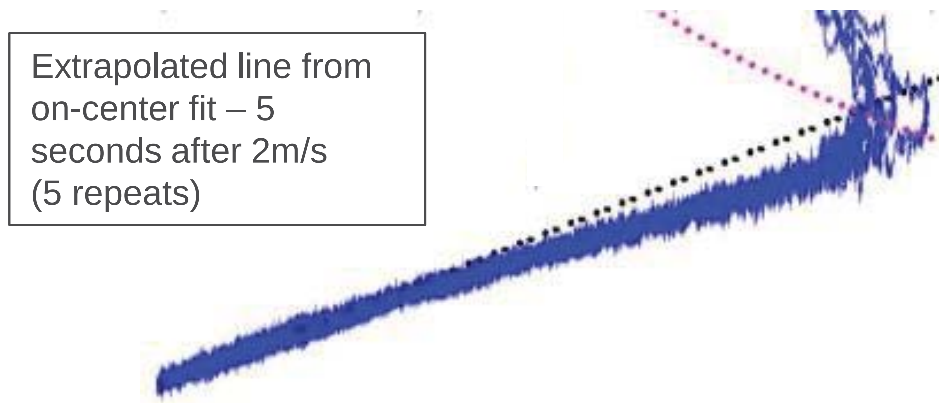
Plotting $0.5g*9.81ms^{-2}$/Vehicle Speed(ms^{-1}) gives a “0.5g Hyperbola” to determine test end

Convergent vehicles typically keep a “substantially constant” slope of yaw rate with speed

Divergent Spin Condition

Instability is shown by a large change in the character (slope) of the plot for a small speed change – it “goes vertical”

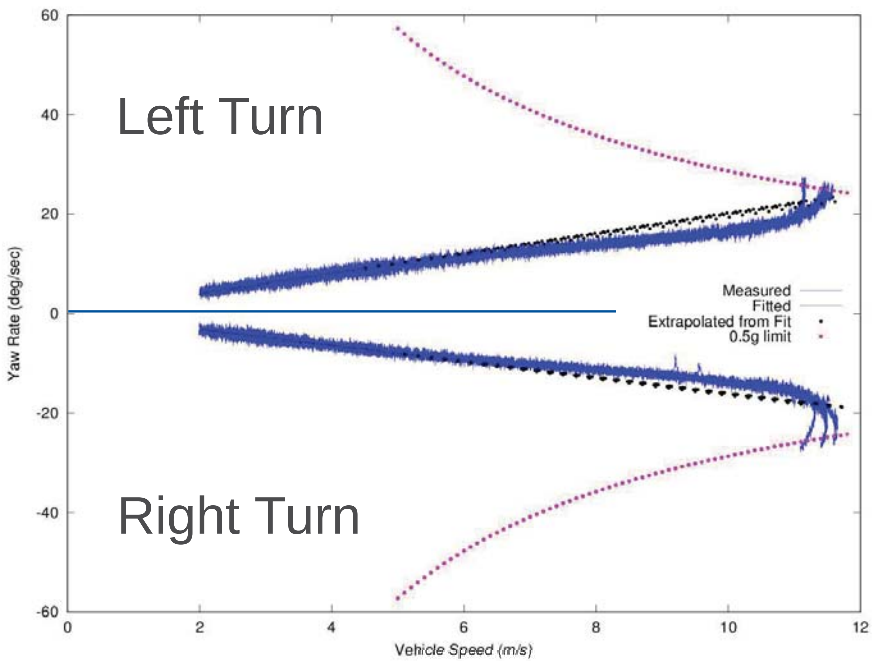


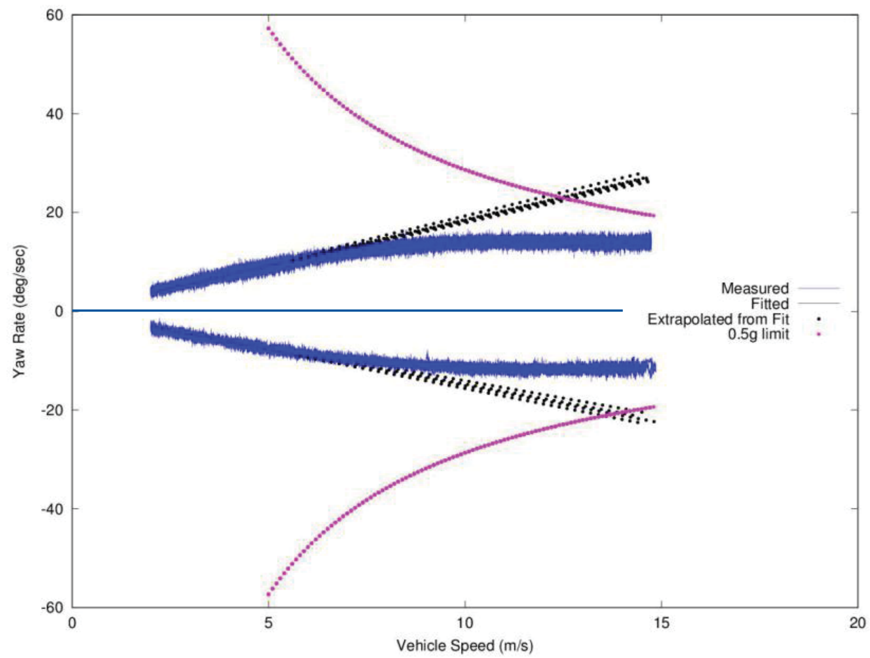


Visually a Strong Difference – No Filtering/Processing Required

200ft Fixed Steer – Divergent/Convergent

- Divergent response – trace "becomes steep" below 0.5g Hyperbola – divergence obvious
- Extremely convergent vehicle – trace goes horizontal
- Both vehicles very consistent in fixed steer test

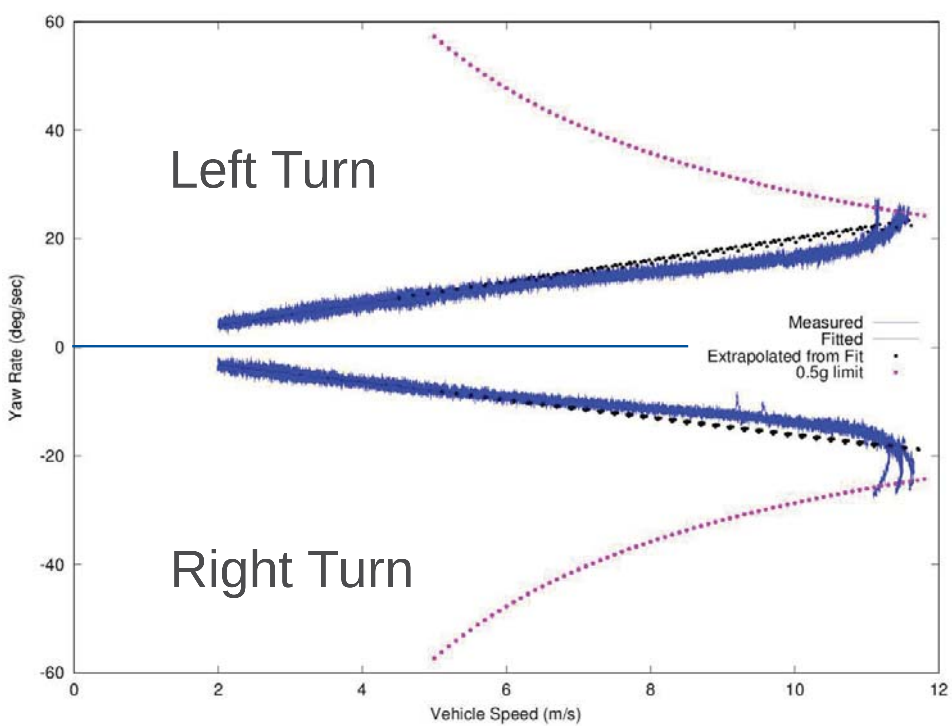


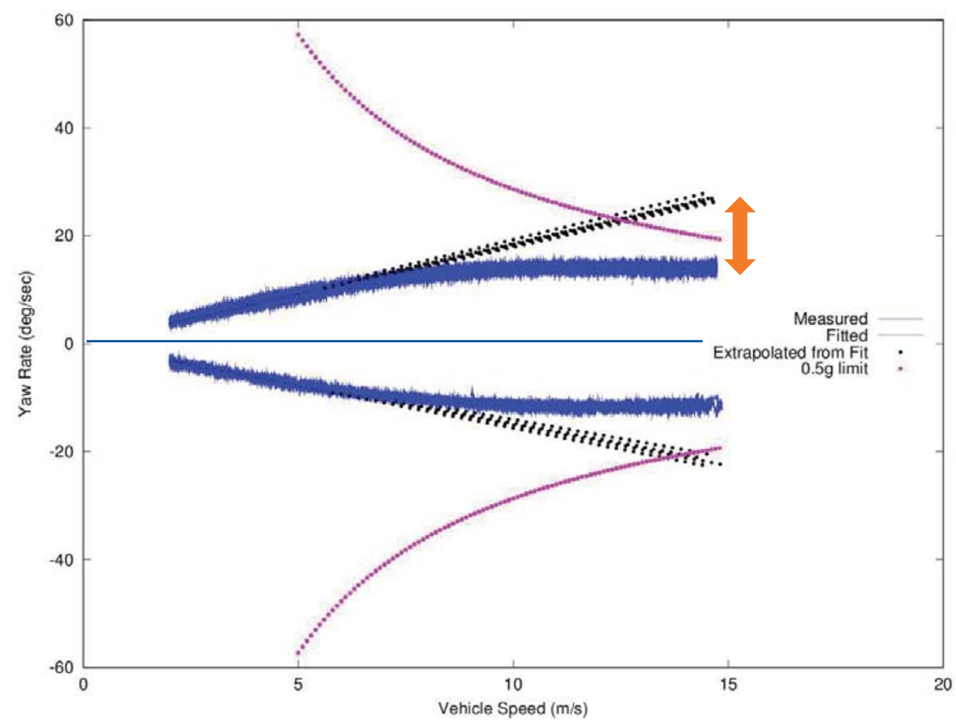


Proposed Test Shows Large Difference

200ft Fixed Steer – Divergent/Convergent

- Note very large increase in yaw rate for 1mph speed change (~0.5 m/s)
- Shows loss of path following ability – "path error" (vehicle is less predictable)



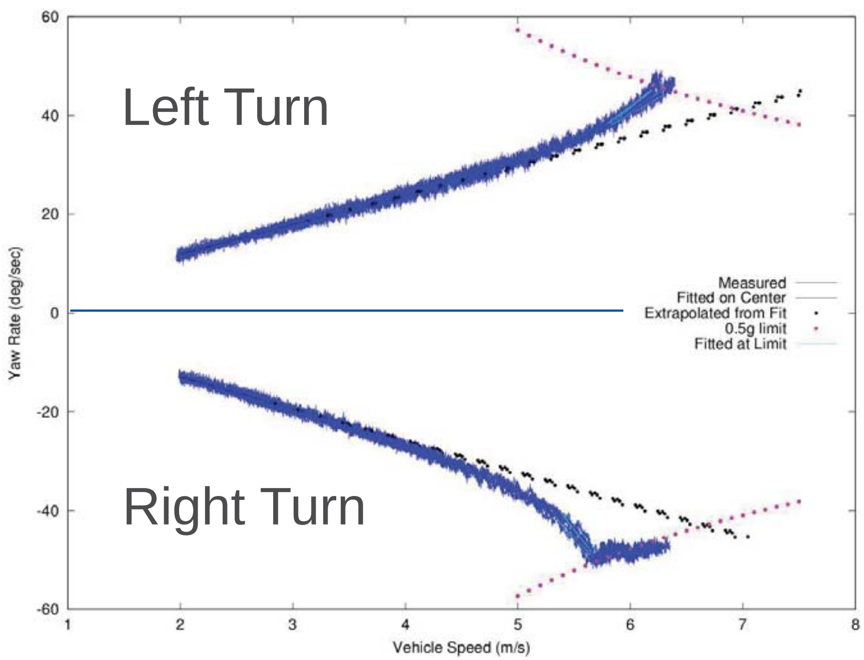


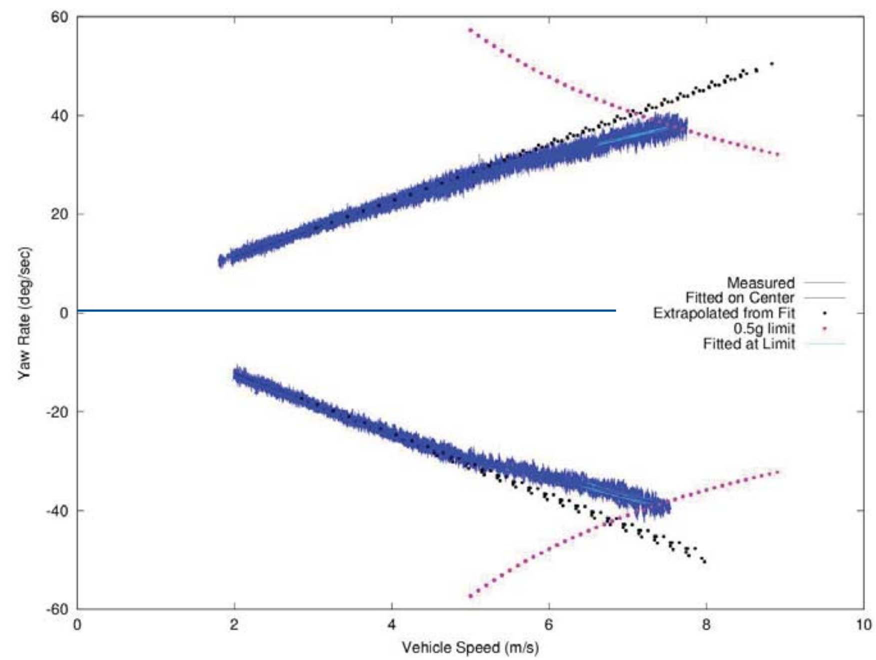
Shows Both Divergence and Path Error Plainly

50ft Fixed Steer – Divergent/Convergent

- Difference still clear - divergent configuration is obvious (vehicle tips onto outriggers on right turn)
- Excellent repeatability always

- Convergence remains clear visually at 0.5g hyperbola for 50ft diameter
- Path following less compromised at low speed





Robust against Test Radius

Suggested Detail - Provisional

Plot 5 repeats in each direction

For each repeat

Fit on-center slope

Fit limit slope

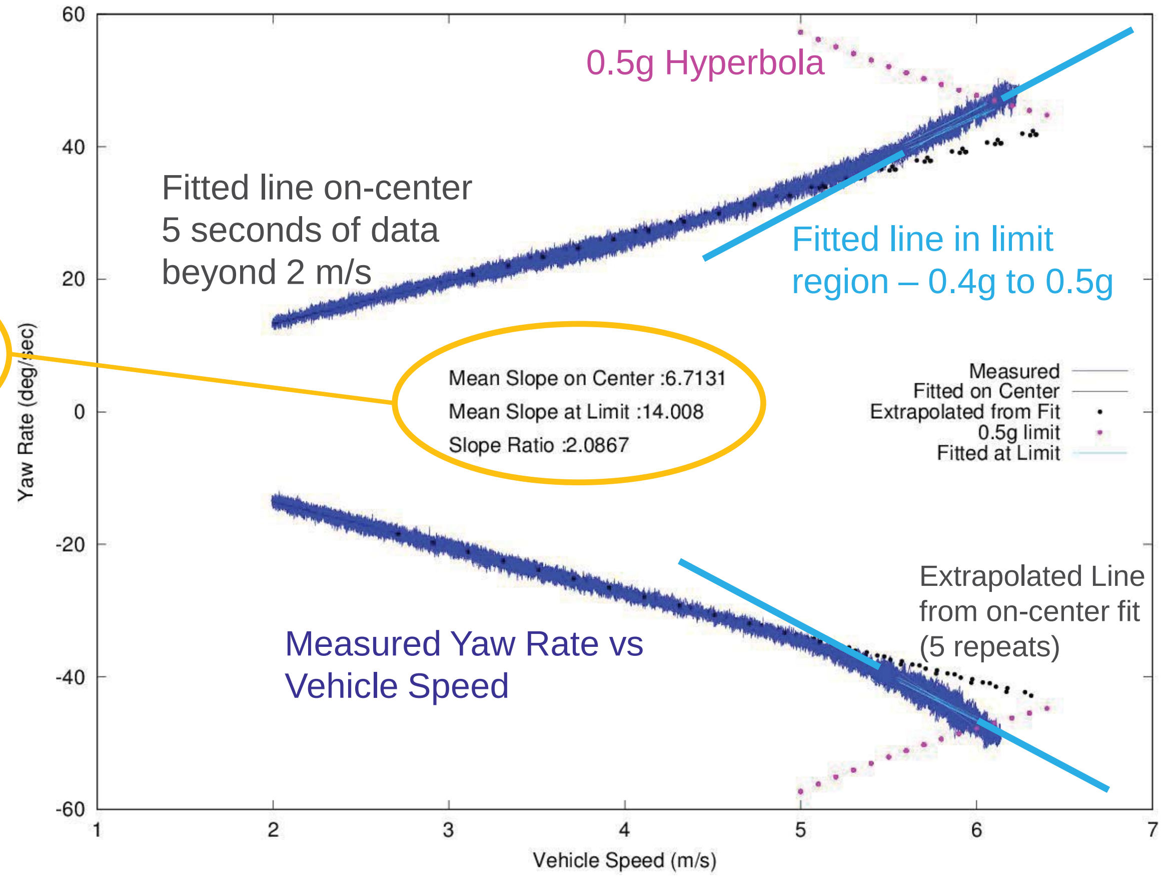
Average on-center slopes between repeats

Average limit slopes between repeats

Evaluate relationship of averaged limit slope to averaged on-center slope

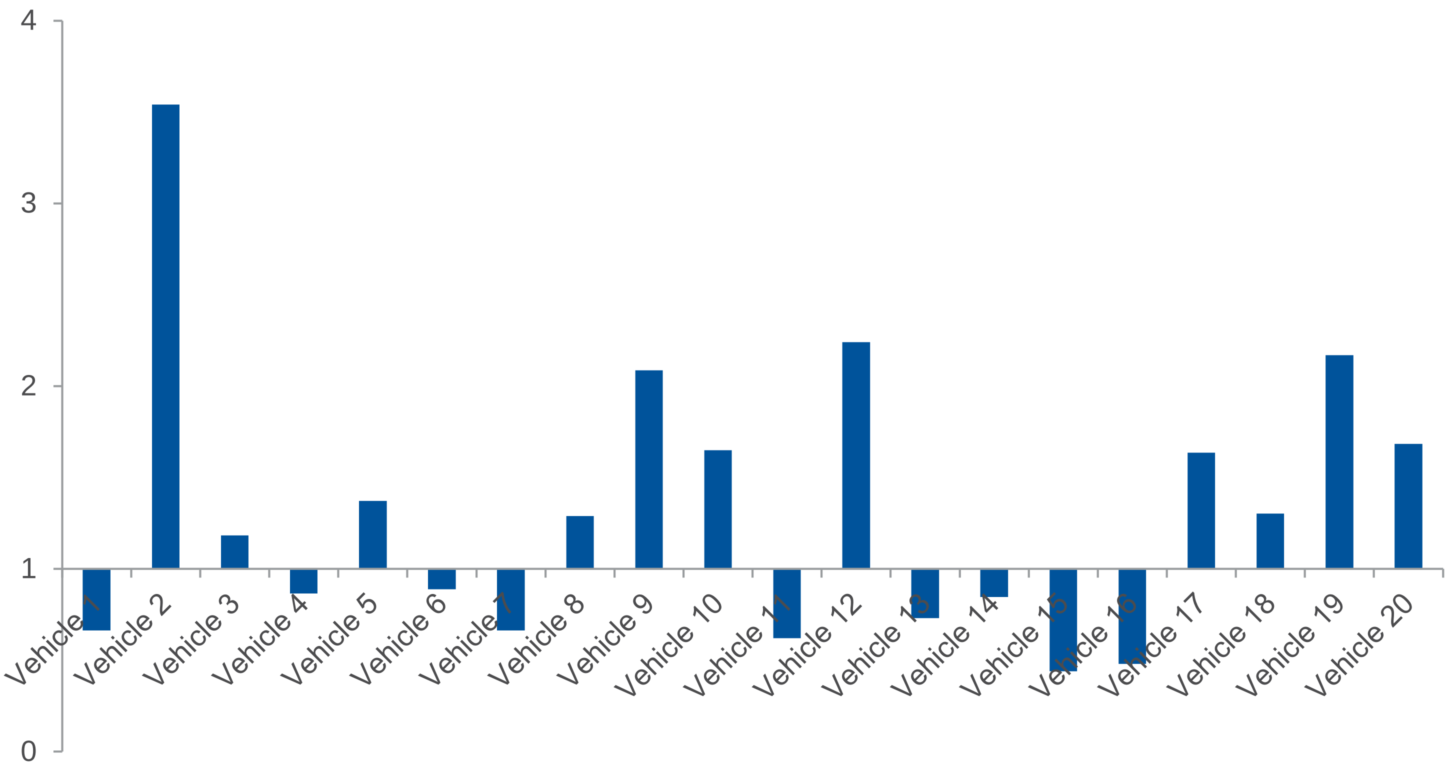
Pass-fail criterion?

Ratio preferred over arithmetical difference – less sensitive to radius



Numerically Robust With Typical Data (20 Vehicle Sample)

Sample Metric – Fleet Review (40/50ft)

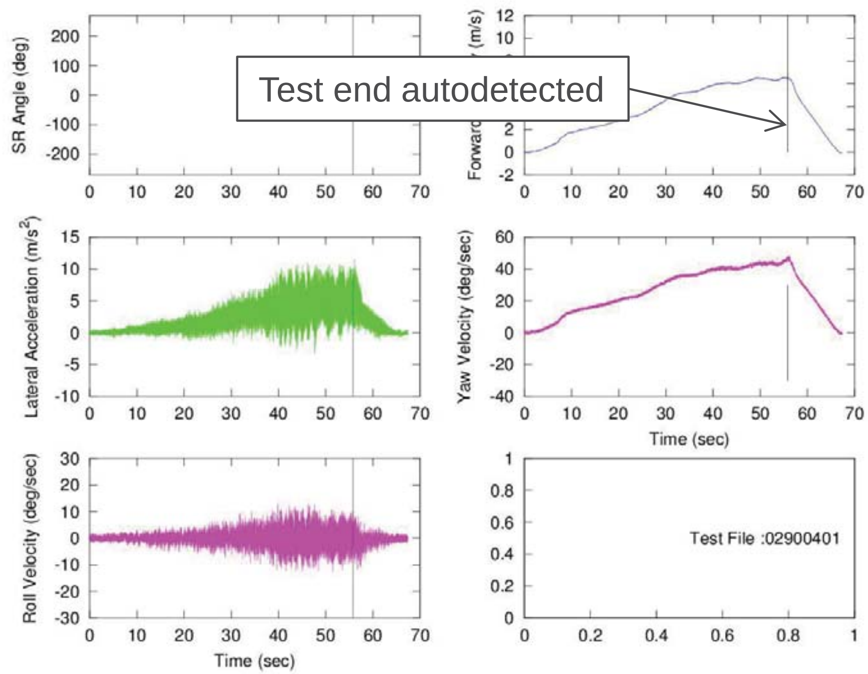


- 200ft circle data shows an even stronger response - ratio of *13.8:1* (Vehicle 2)
- 100ft circle expected to be somewhere between the two
- 100ft probably reflects a good compromise between space required and quality of results
- All vehicles converge except Vehicle 2 (spins)
- Not all vehicles are understeer

Divergent Response Stands Out in Blind, Automated Processing

Process Automation

- **Test end detection – characteristic goes through 0.55g hyperbola or significant deceleration**



- **Limit identification – 0.5g Hyperbola crossing or maximum inferred Lateral Acceleration (some vehicles don't make 0.5g)**
- **Fit window controllable – uses 0.1g in examples so far**

```
% 0.5g limit hard coded in standard - lower limit is optional
limits=[0.5*9.81 0.5*9.81-slope2FitAccel];

for limloop=1:2
  if max(abs(LatAccEstFilt)) < limits(limloop)
    [maxAcc limCount(limloop)]=max(abs(LatAccEstFilt));
  else
    if max(diff(find(abs(LatAccEstFilt) < limits(limloop)))) > 1
      % Find the last time the vehicle is under 0.5g for contiguous data points
      limCount(limloop)=min(find(diff(find(abs(LatAccEstFilt) < limits(limloop)))>1));
    else
      % If this test fails, find the last time the vehicle is under 0.5g
      limCount(limloop) = max(find(abs(LatAccEstFilt) < limits(limloop)));
    endif
  endif
endfor
X1(file_num)=FwdVelFilt(limCount(2));
X2(file_num)=FwdVelFilt(limCount(1));
A = [ForwardVelocity(limCount(2):limCount(1)) ones(limCount(1)-limCount(2)+1,1)];
mc = A \ YawVelocity(limCount(2):limCount(1));

% Store slope and intercept for this file
slope2(file_num) = mc(1);
intercept2(file_num) = mc(2);
```

Process Automates Well

Next Steps

100ft Data Comparison

Expand Vehicle set

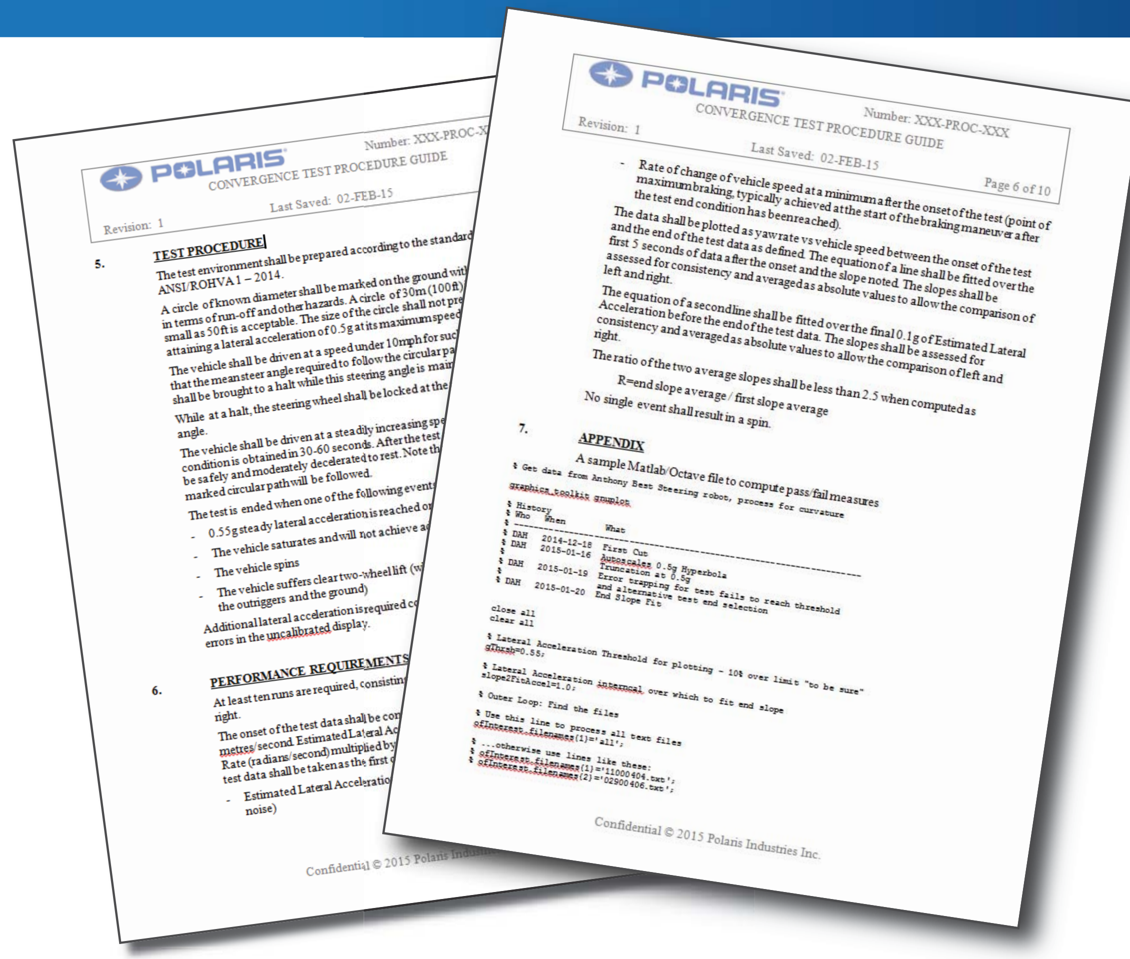
eg Historic

Test robustness of processing

Refine Pass/Fail criteria

Formalize Process

Receive Inputs from others


POLARIS CONVERGENCE TEST PROCEDURE GUIDE
Number: XXX-PROC-X
Revision: 1
Last Saved: 02-FEB-15

5. TEST PROCEDURE

The test environment shall be prepared according to the standard ANSI/ROHVA 1 – 2014.

A circle of known diameter shall be marked on the ground wit in terms of run-off and other hazards. A circle of 30m (100ft) small as 50ft is acceptable. The size of the circle shall not pre attaining a lateral acceleration of 0.5g at its maximum speed

The vehicle shall be driven at a speed under 10mph for suc that the mean steer angle required to follow the circular pa shall be brought to a halt while this steering angle is main

While at a halt, the steering wheel shall be locked at the angle.

The vehicle shall be driven at a steadily increasing sp condition is obtained in 30-60 seconds. After the test be safely and moderately decelerated to rest. Note th marked circular path will be followed.

The test is ended when one of the following event

- 0.55g steady lateral acceleration is reached or
- The vehicle saturates and will not achieve a
- The vehicle spins
- The vehicle suffers clear two-wheel lift (w the outriggers and the ground)

Additional lateral acceleration is required c errors in the uncalibrated display.

6. PERFORMANCE REQUIREMENTS

At least ten runs are required, consistin right.

The onset of the test data shall be cor metres/second. Estimated Lateral Ac Rate (radians/second) multiplied by test data shall be taken as the first c

- Estimated Lateral Acceleratio noise)

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- Rate of change of vehicle speed at a minimum after the onset of the test (point of maximum braking, typically achieved at the start of the braking maneuver after the test end condition has been reached).

The data shall be plotted as yaw rate vs vehicle speed between the onset of the test and the end of the test data as defined. The equation of a line shall be fitted over the first 5 seconds of data after the onset and the slope noted. The slopes shall be assessed for consistency and averaged as absolute values to allow the comparison of left and right.

The equation of a second line shall be fitted over the final 0.1g of Estimated Lateral Acceleration before the end of the test data. The slopes shall be assessed for consistency and averaged as absolute values to allow the comparison of left and right.

The ratio of the two average slopes shall be less than 2.5 when computed as

R=end slope average / first slope average

No single event shall result in a spin.

7. APPENDIX

A sample Matlab/Octave file to compute pass/fail measures

```
% Get data from Anthony Best Steering robot, process for curvature
close all
clear all
% Lateral Acceleration Threshold for plotting - 10% over limit "to be sure"
% Lateral Acceleration interval over which to fit end slope
% Outer Loop: Find the files
% Use this line to process all text files
% ...otherwise use lines like these:
```

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Early Promise Needs Verification & Formalization

Summary

Method developed on first principles/best-practices

Better Surrogate for Tripped Rollover Risk

Repeatable methods with minimal test errors

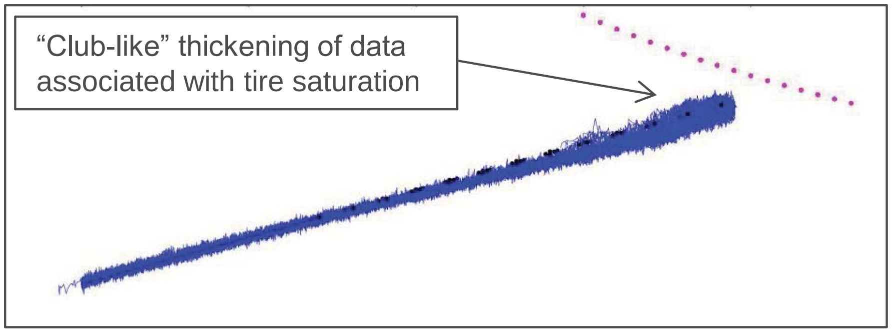
Drives predictable vehicle handling designs

Discriminates and identifies unpredictable behaviors

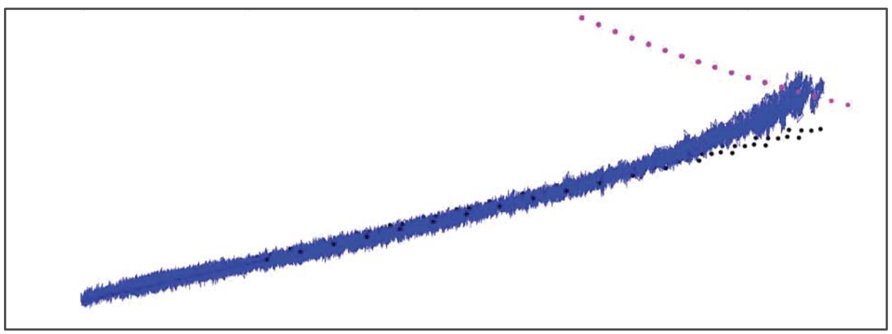
Superior Alternative to Understeer Bias

Broad Picture of Vehicle

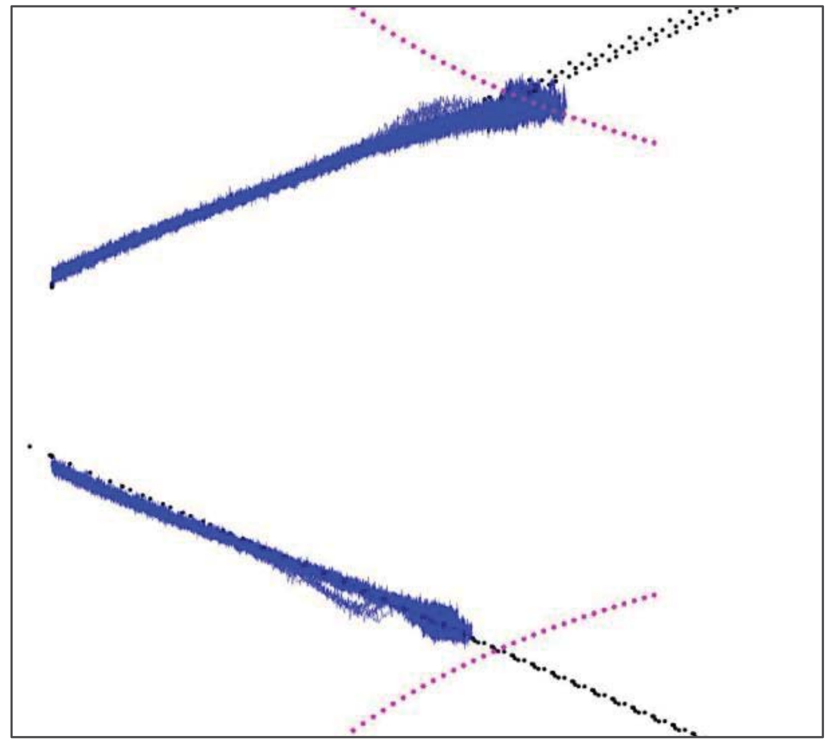
- **What other signatures can the data show?**
  - Fails to reach 0.5g



  - Convergent oversteer



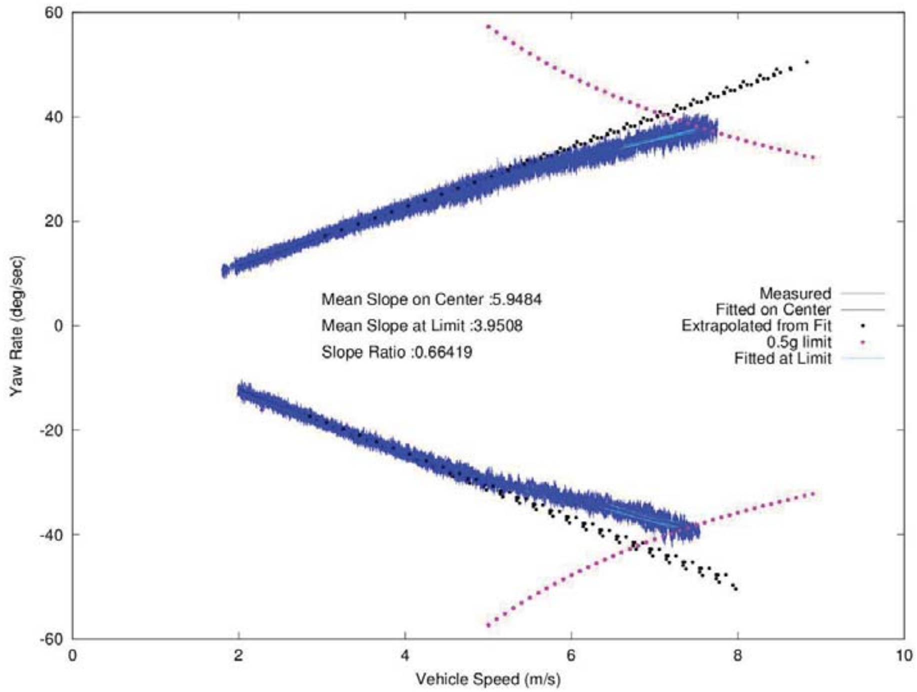
  - Lack of symmetry left-to-right



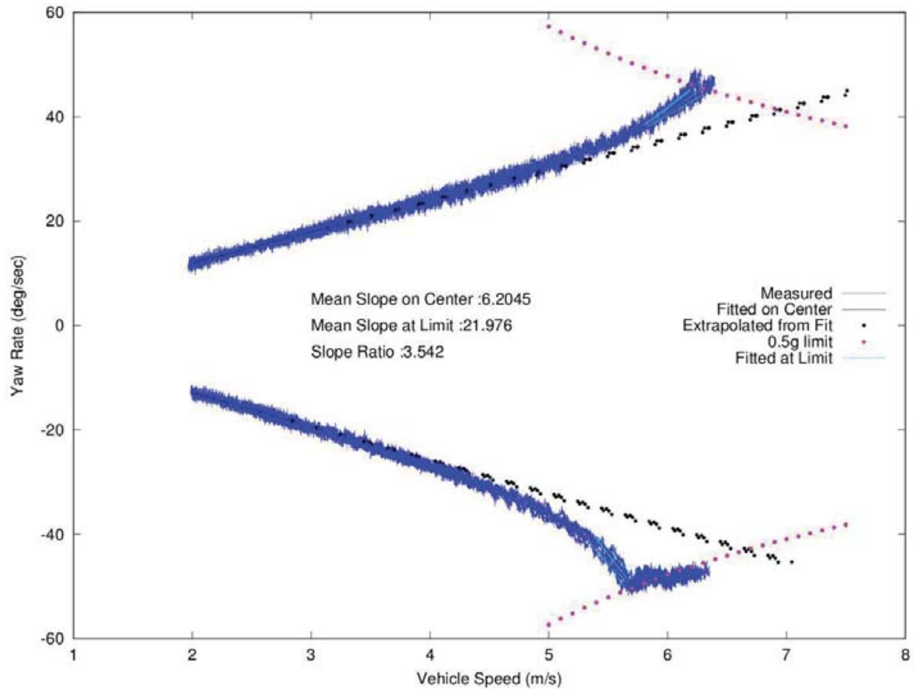
Other Numerical Measures of Interest to Manufacturers are Possible

Appendix – Real Vehicle Data – 50ft

- Vehicle 1



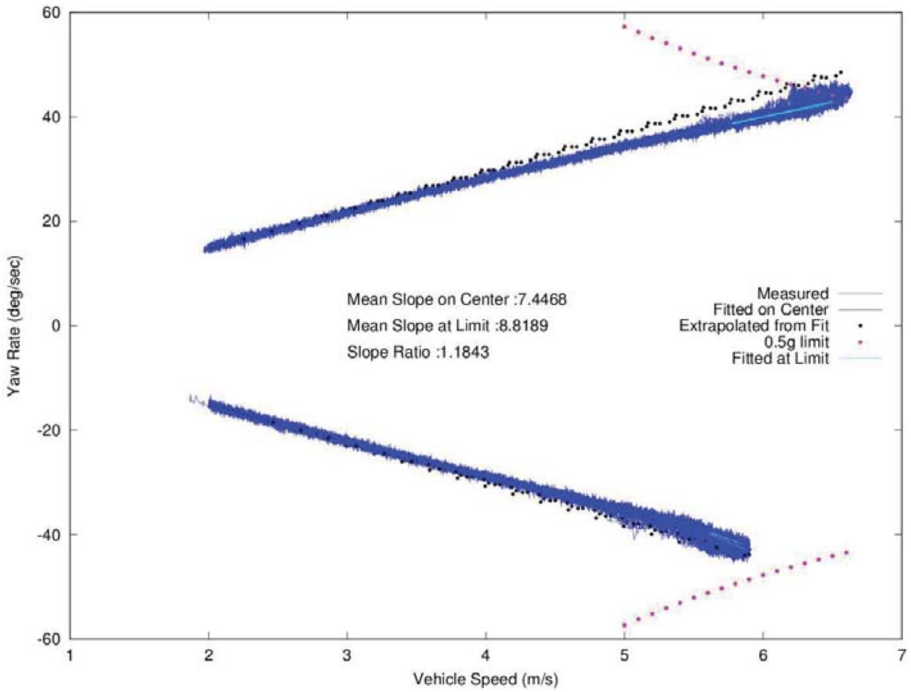
- Vehicle 2



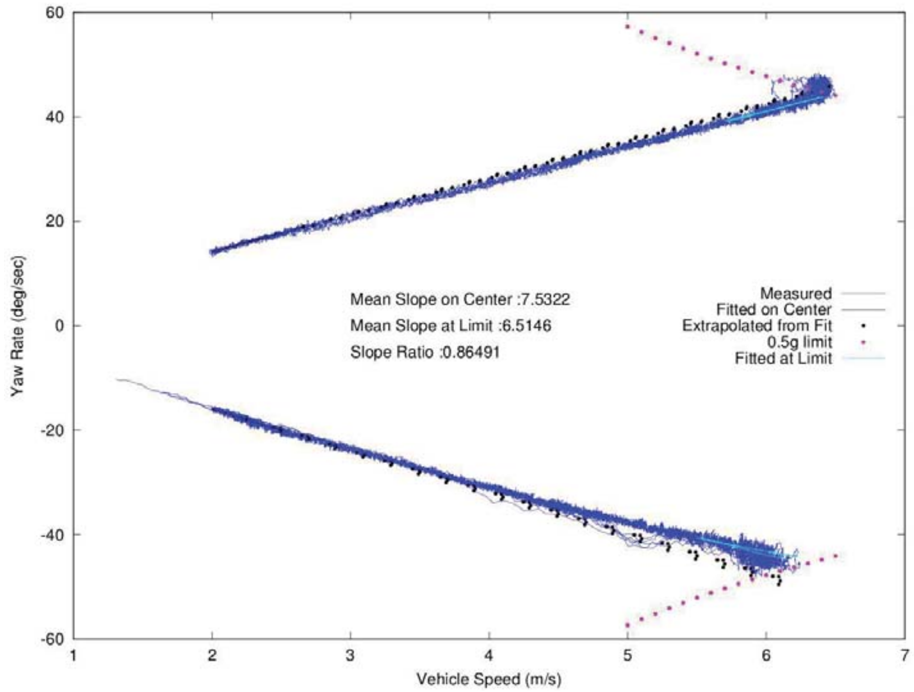
Appendix – Real Vehicle Data – 50ft

Appendix – Real Vehicle Data – 50ft

- Vehicle 3



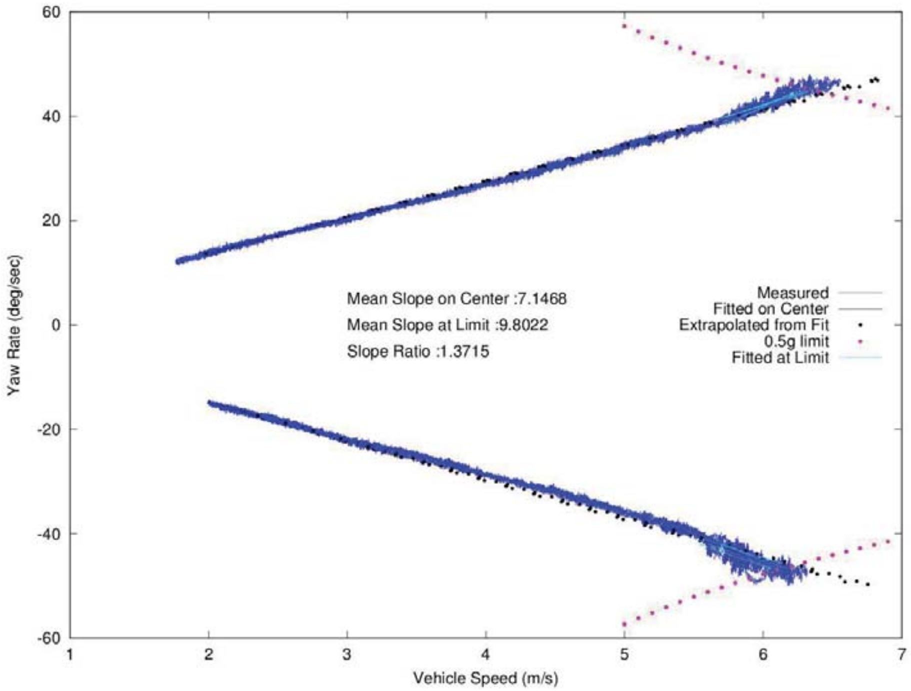
- Vehicle 4



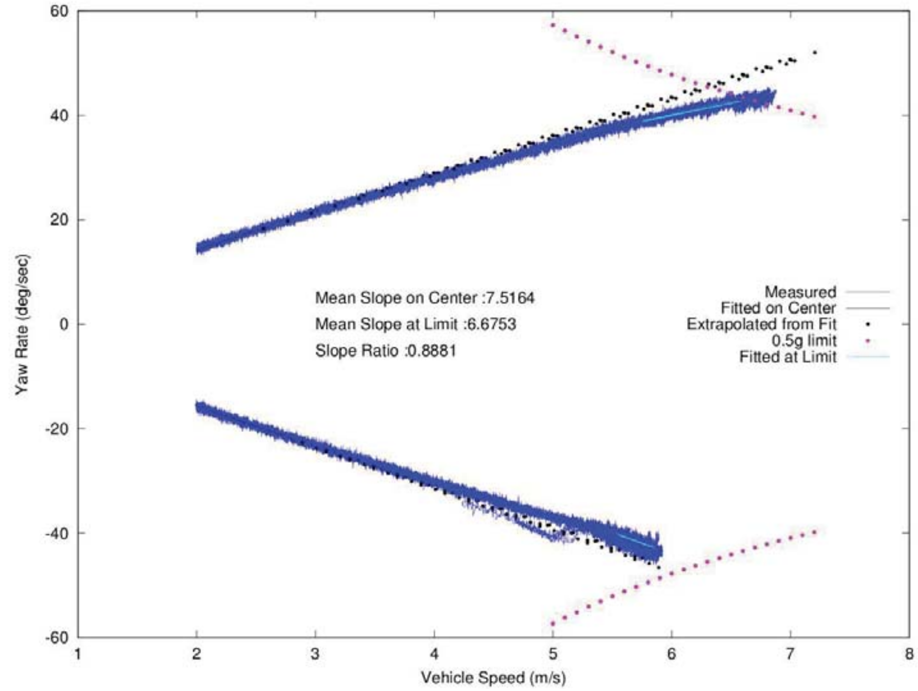
Appendix – Real Vehicle Data – 50ft

Appendix – Real Vehicle Data – 50ft

- Vehicle 5



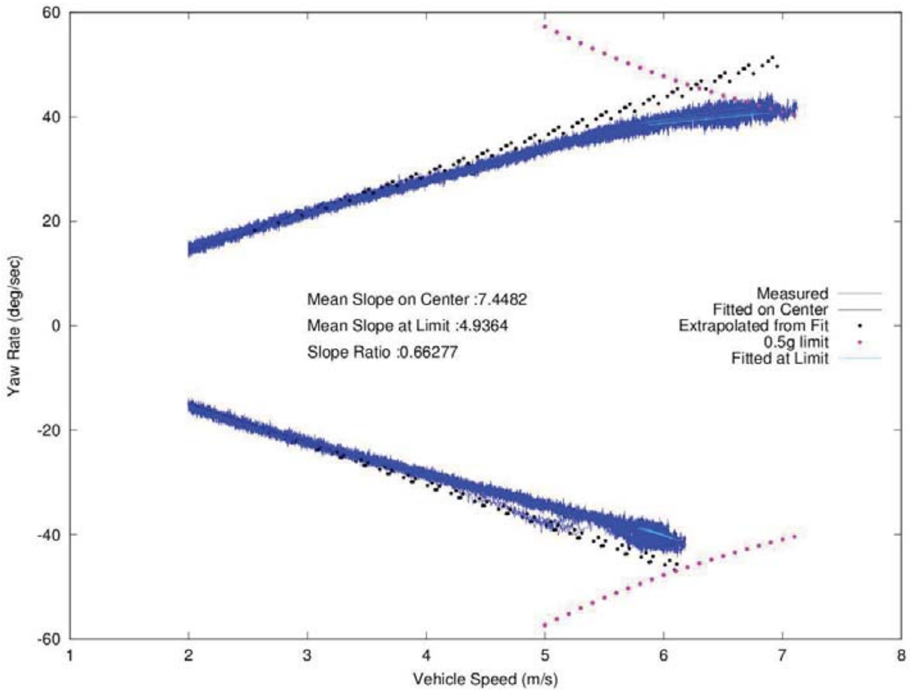
- Vehicle 6



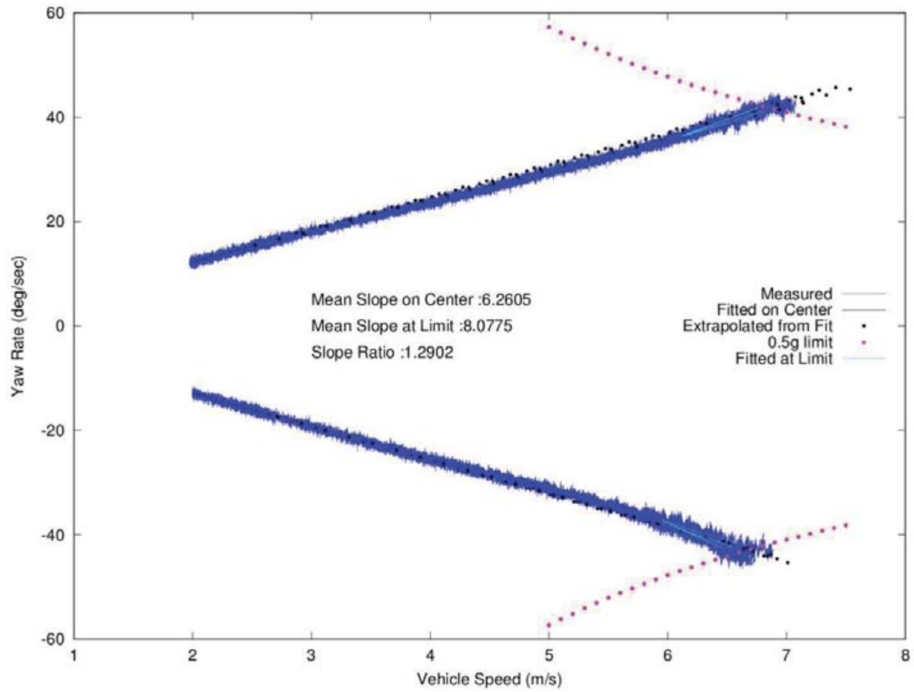
Appendix – Real Vehicle Data – 50ft

Appendix – Real Vehicle Data – 50ft

- Vehicle 7



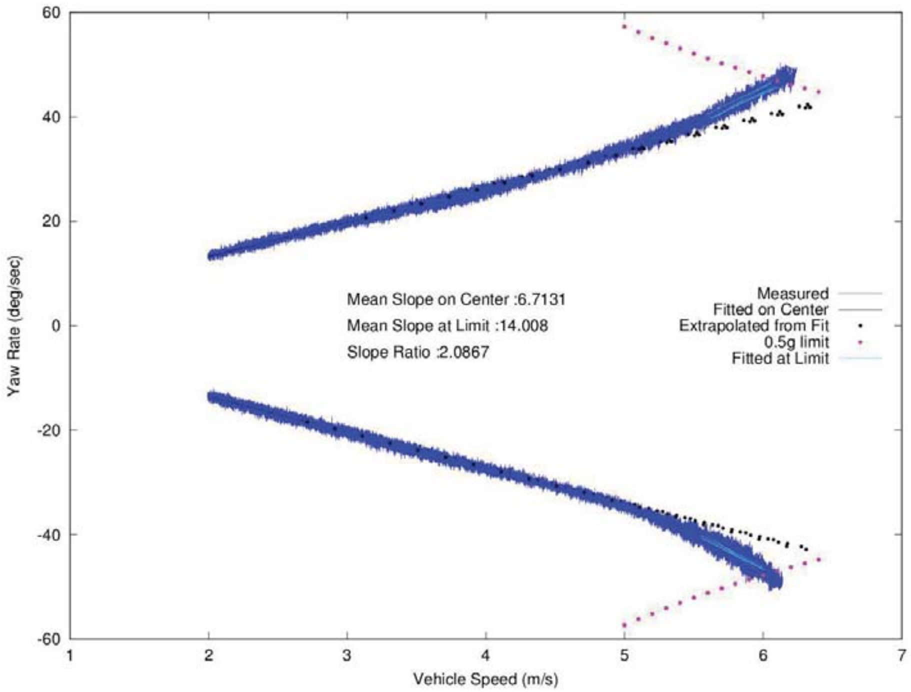
- Vehicle 8



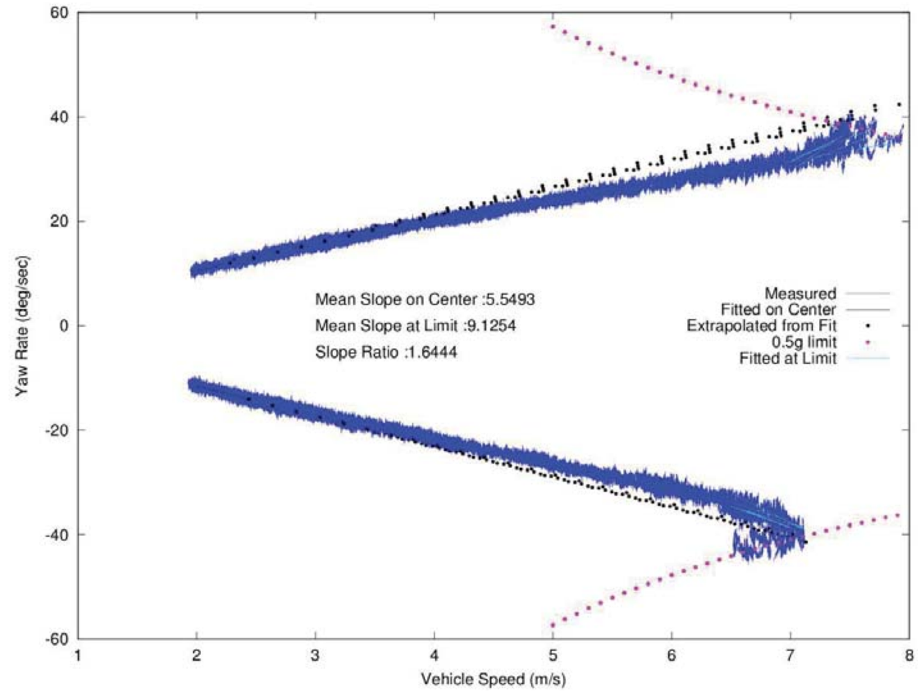
Appendix – Real Vehicle Data – 50ft

Appendix – Real Vehicle Data – 50ft

- Vehicle 9



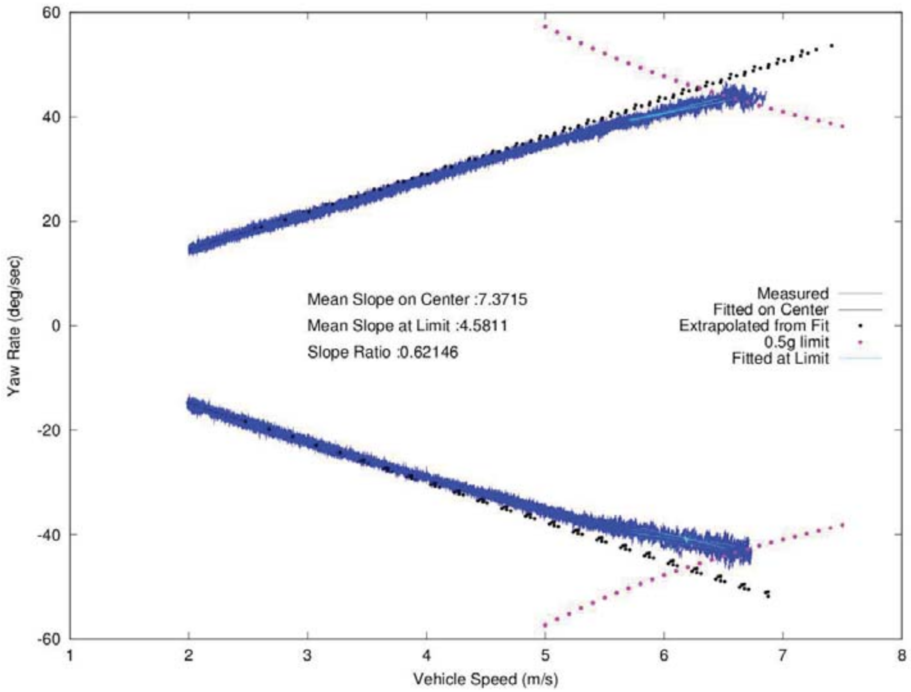
- Vehicle 10



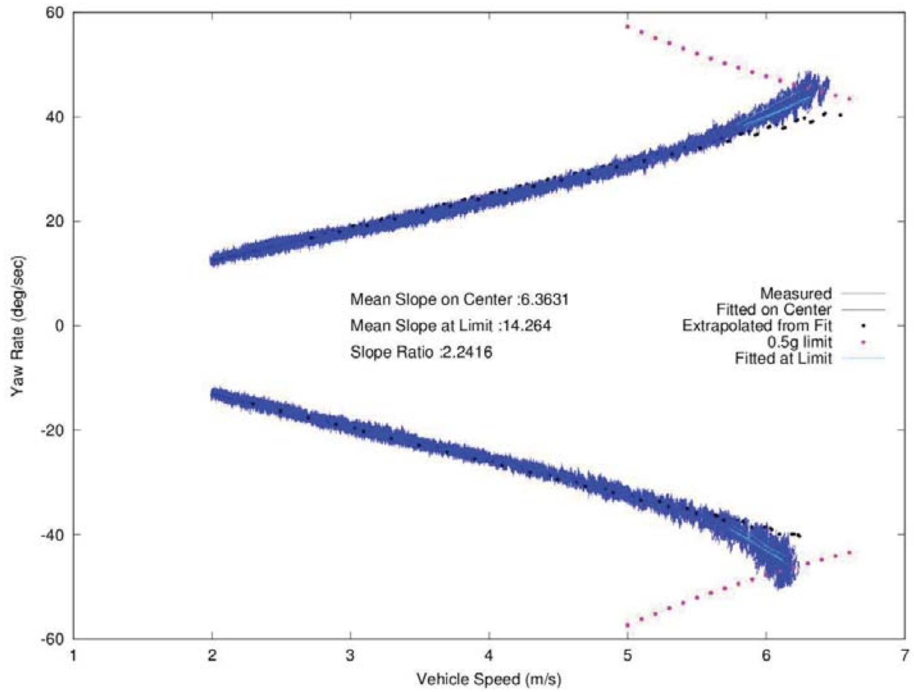
Appendix – Real Vehicle Data – 50ft

Appendix – Real Vehicle Data – 50ft

- **Vehicle 11**



- **Vehicle 12**



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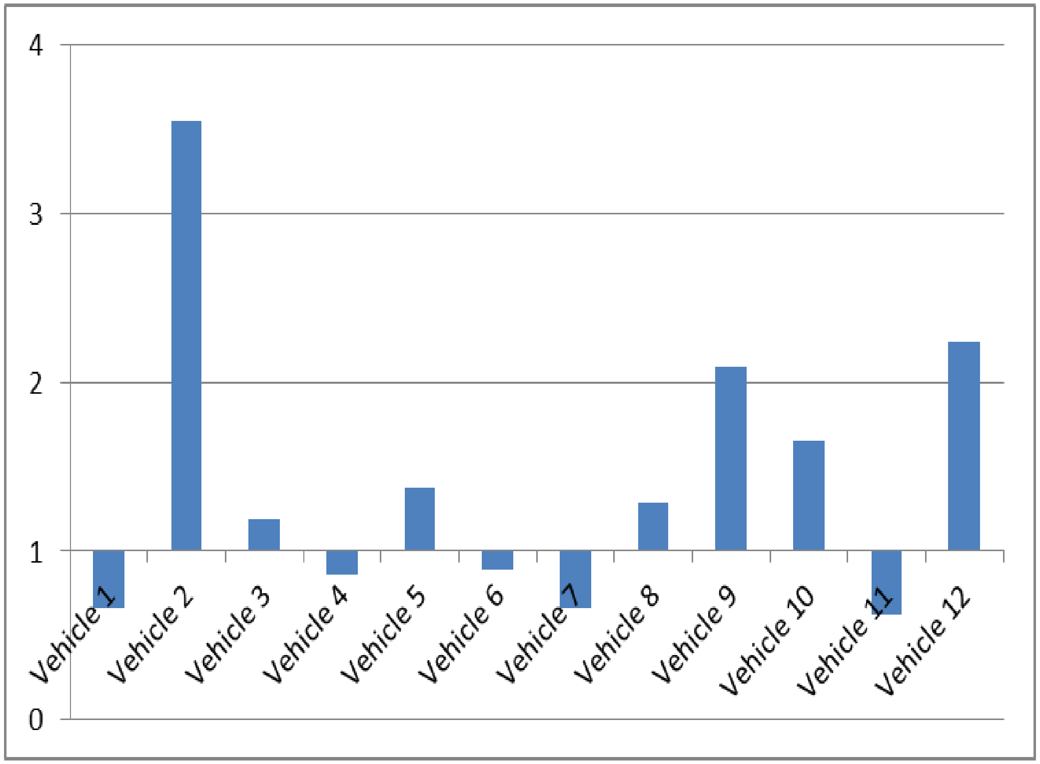


- **Summary**
- Ratio and Delta measures tell the same story (ratio plot shown)
- All vehicles converge except Vehicle 2

J-Turn Discussion

NHTSA Rollover Definitions

UN-TRIPPED

Un-tripped rollovers are less common than tripped rollovers, **occurring less than 5%** of the time, and mostly to top-heavy vehicles. Instead of an object serving as a tripping mechanism, un-tripped rollovers **usually occur during high-speed collision avoidance maneuvers.**

TRIPPED ROLLOVERS

NHTSA data show that **95% of single-vehicle rollovers are tripped**. This happens when a vehicle leaves the roadway and **slides sideways**, digging its tires into soft soil or striking an object such as a curb or guardrail. The high tripping force applied to the tires in these situations can cause the vehicle to roll over.

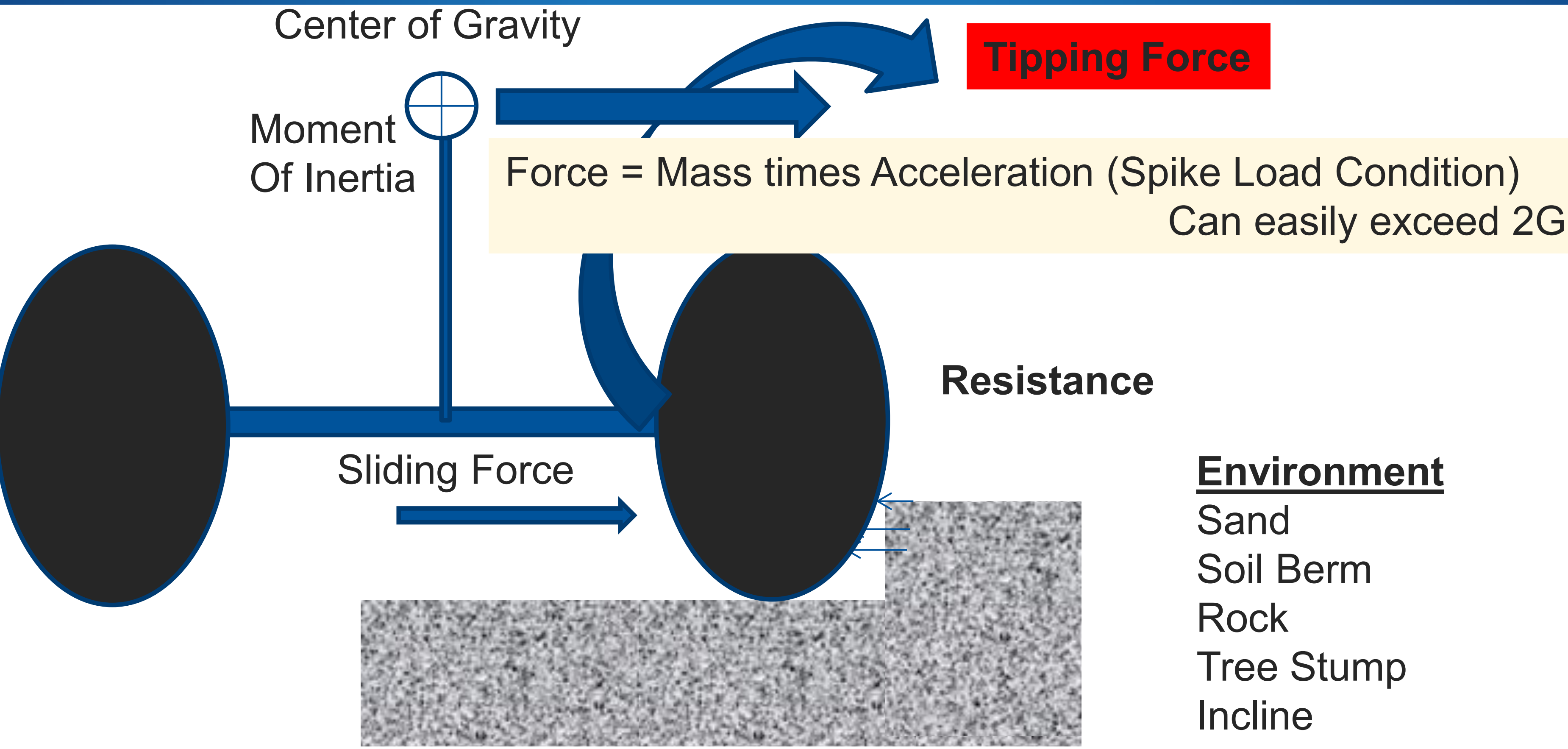
Soft Soil

Steep Slope

Guardrail

From safecar.gov Website

Off Road Vehicle Tripping Condition



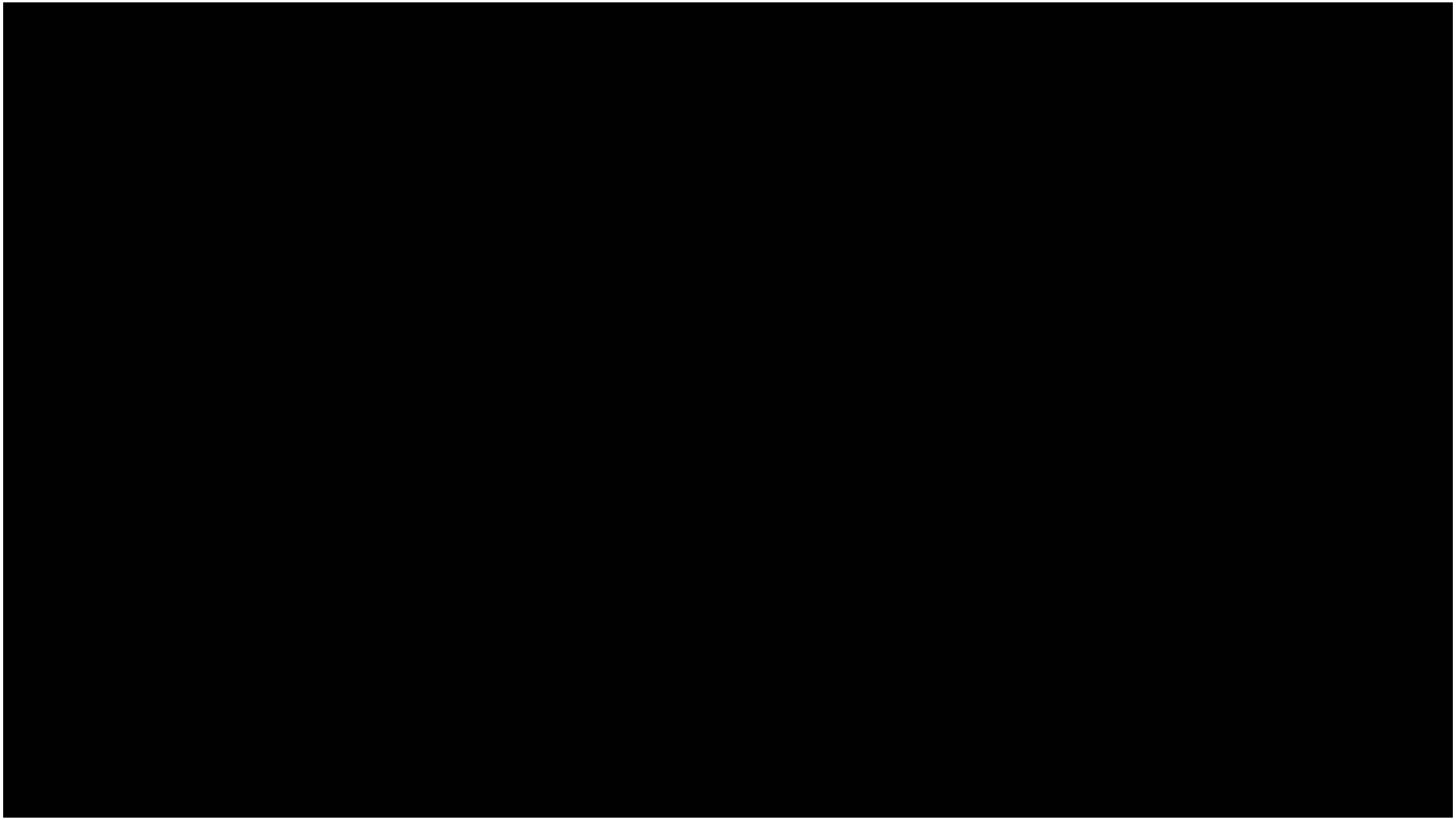
Off Road driving conditions can result in a tripping condition

http://www.safercar.gov/Vehicle+Shoppers/Rollover/Types+of+Rollovers

NPR Ay Requirement Can Not Prevent Tripping Rollovers

Sand J-Turn Video

Off Road Vehicle Division



Video shown at half speed – actually traveling 25mph

Off-Road Testing

Sand

DESCRIPION: 60' x 60' pad 6" deep with sand. Sand was frozen during testing and was only loose on the top 1"-2".

Vehicle Set-Up	Test Speed	Roll Steer Angle		No Roll Steer Angle	
	(mph)	Run #	(degree)	Run #	(degree)
Open Rear Differential	25	12	200		
Locked Rear Differential	28.5	19	300		

Gravel

DESCRIPION: 60' x 60' pad 6" deep with 0.5" - 0.75" gravel. Gravel was frozen during testing and was only loose on the top 1

Vehicle Set-Up	Test Speed	Roll Steer Angle		No Roll Steer Angle	
	(mph)	Run #	(degree)	Run #	(degree)
Open Rear Differential	27.5	29	190	28	170
Locked Rear Differential	27.5	26	280	25	250
No Rear Bar Open Diff	27.5	34	250	33	230
No Rear Bar Locked Diff	30	40	290	39	280

Notes:

1) **On pavement, the locked differential is oversteer and the open differential is understeer**
2) **In sand and gravel, the understeered vehicle rolled much easier than the oversteered vehicle**

Off-road behaviors can vary greatly from on-road – unintended consequences

Off-Road Testing

Off Road Vehicle Division

Plowed Dirt

DESCRIPION: 60' x 60' pad chisel plowed field dirt. Large frozen clumps roughly 6" in diameter.

Vehicle Set-Up	Test Speed (mph)	Roll Steer Angle Run #	Roll Steer Angle (degree)	No Roll Steer Angle Run #	No Roll Steer Angle (degree)
Open Rear Differential	27.5	44	130	43	120
Locked Rear Differential	27.2	46	120		

Grass Field

DESCRIPION: Frozen grass field with patches of snow. Field was very lumpy and uneven.

Vehicle Set-Up	Test Speed (mph)	Roll Steer Angle Run #	Roll Steer Angle (degree)	No Roll Steer Angle Run #	No Roll Steer Angle (degree)
Open Rear Differential	27.2	48	110	50	95
Locked Rear Differential	27.2			51	110

Pavement

DESCRIPION: Polaris asphault test pad in Roseau, MN.

Vehicle Set-Up	Test Speed (mph)	Roll Steer Angle Run #	Roll Steer Angle (degree)	No Roll Steer Angle Run #	No Roll Steer Angle (degree)
Open Rear Differential	30		150		145
Locked Rear Differential	30		170		165
*No Rear Bar Open Diff	30		185		180
*No Rear Bar Locked Diff	30		225		220

*data from a different vehicle - same model but different VIN

Notes:

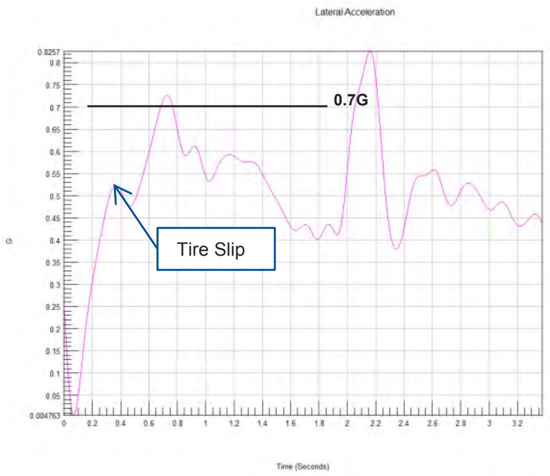
1) On pavement, the locked differential is oversteer and the open differential is understeer

2) As the surface roughness increased, less steering angle was required and the differential position had less effect

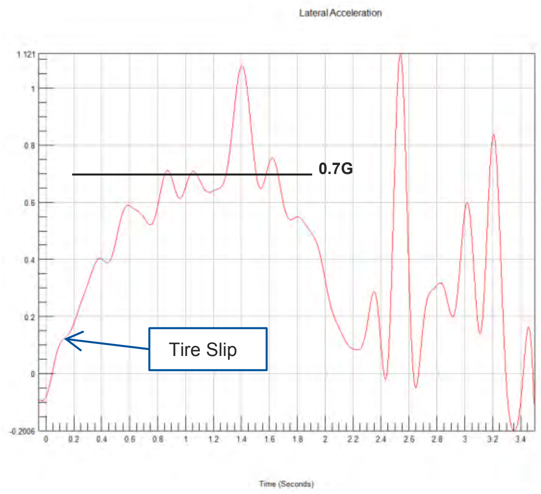
Off-road behaviors can vary greatly from on-road – unintended consequences

Lateral Acceleration Comparison

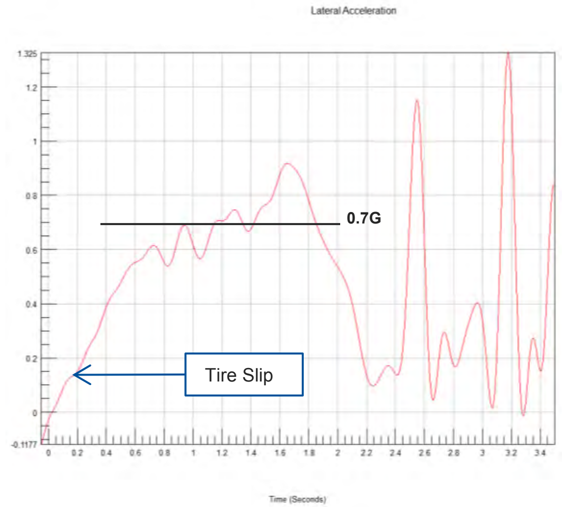
Pavement (Peak Ay @ .72)



Sand (Peak Ay @ 1.1)



Gravel (Peak Ay @ 0.9)



All runs shown ended in roll:

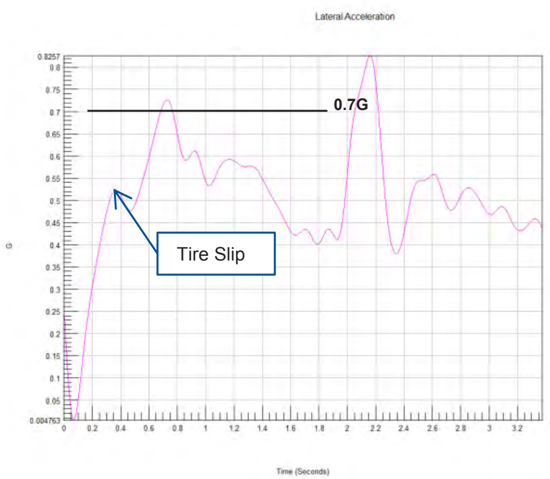
- Off-road runs begin sliding at less than 0.3G and can reach lateral accelerations well above 1.0
- Spikes are noticeable of the tire tripping/skipping over the ground
- Once the vehicle begins sliding, well below 0.3G, it really doesn’t matter what its Ay on pavement is because it will trip and spike well above that value

Sliding Begins Well Below 0.7 G, Tripping Occurs Well Above 0.7G

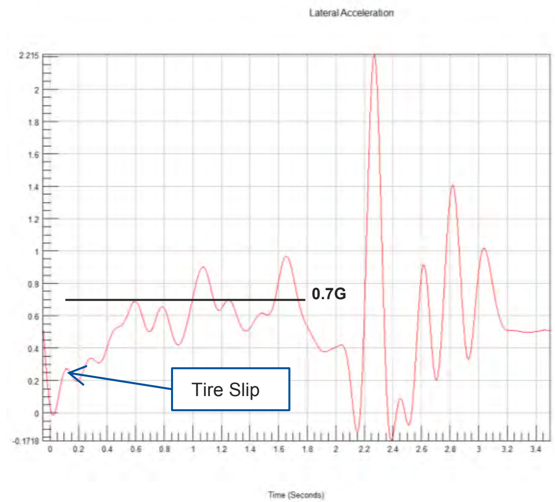
Lateral Acceleration Comparison

Off Road Vehicle Division

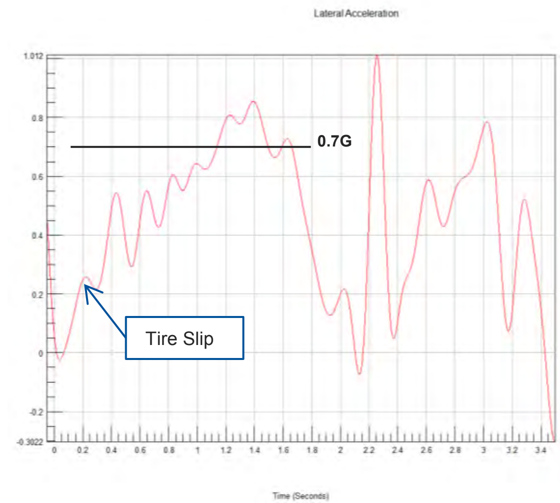
Pavement (Peak Ay @ .72)



Plowed Dirt (Peak Ay @ 0.96)



Rough Grass (Peak Ay @ 0.87)



All runs shown ended in roll:

- Off-road runs begin sliding at less than 0.3G and can reach lateral accelerations well above 1.0
- Spikes are noticeable of the tire tripping/skipping over the ground
- Once the vehicle begins sliding, well below 0.3G, it really doesn’t matter what its Ay on pavement is because it will trip and spike well above that value

Sliding Begins Well Below 0.7 G, Tripping Occurs Well Above 0.7G

Summary

- **Vast majority of Off-Road rollovers are tripped**
- **On-Road J-Turn does not predict tripped rollover resistance**
- **Off-road terrain causes tires to slip well below 0.7g, proposed threshold is not connected to the terrain failure limit**
  - Once tires begin to slip, a tripped rollover is highly likely
  - Lateral acceleration at trip is well above .7g
- **Steer input at roll consistently higher off road vs on pavement**
- **Focus vehicle designs to increase slip resistance & improve handling predictability**

Steer input on Pavement Is A Better Pass/Fail Metric