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:

<table>
<thead>
<tr>
<th>NAME</th>
<th>ORGANIZATION</th>
<th>PHONE</th>
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<tbody>
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<thead>
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A Handling Quality Metric
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**


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
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]:

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

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

[4] Newton’s 2nd Law

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)
“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
Detecting Divergence – Fixed Steer Results

No Spin Condition

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

Plotting $0.5g \times 9.81 \text{ ms}^{-2}/\text{Vehicle Speed (ms}^{-1})$ 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

Left Turn

Right Turn
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)

Left Turn

Right Turn

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
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)
Divergent Response Stands Out in Blind, Automated Processing

- 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
• 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
Next Steps

100ft Data Comparison
Expand Vehicle set eg Historic
Test robustness of processing
Refine Pass/Fail criteria
Formalize Process
Receive Inputs from others

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

  "Club-like" thickening of data associated with tire saturation

- 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

- Vehicle 3

- Vehicle 4
Appendix – Real Vehicle Data – 50ft

- Vehicle 5

- Vehicle 6
Appendix – Real Vehicle Data – 50ft

- Vehicle 7

- Vehicle 8
Appendix – Real Vehicle Data – 50ft

• Vehicle 9

• Vehicle 10
Appendix – Real Vehicle Data – 50ft

• Vehicle 11

• Vehicle 12
• **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.
Off Road Vehicle Tripping Condition

Off Road driving conditions can result in a tripping condition

Environment
Sand
Soil Berm
Rock
Tree Stump
Incline

Force = Mass times Acceleration (Spike Load Condition)
Can easily exceed 2G

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

NPR Ay Requirement Can Not Prevent Tripping Rollovers
Sand J-Turn Video

Video shown at half speed – actually traveling 25mph
Off-Road Testing

Sand

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

<table>
<thead>
<tr>
<th>Vehicle Set-Up</th>
<th>Test Speed (mph)</th>
<th>Roll Steer Angle (degree)</th>
<th>No Roll Steer Angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Rear Differential</td>
<td>25</td>
<td>12</td>
<td>200</td>
</tr>
<tr>
<td>Locked Rear Differential</td>
<td>28.5</td>
<td>19</td>
<td>300</td>
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Gravel

DESCRIPTION: 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"-2".

<table>
<thead>
<tr>
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<th>Test Speed (mph)</th>
<th>Roll Steer Angle (degree)</th>
<th>No Roll Steer Angle (degree)</th>
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<tbody>
<tr>
<td>Open Rear Differential</td>
<td>27.5</td>
<td>29</td>
<td>190</td>
</tr>
<tr>
<td>Locked Rear Differential</td>
<td>27.5</td>
<td>26</td>
<td>280</td>
</tr>
<tr>
<td>No Rear Bar Open Diff</td>
<td>27.5</td>
<td>34</td>
<td>250</td>
</tr>
<tr>
<td>No Rear Bar Locked Diff</td>
<td>30</td>
<td>40</td>
<td>290</td>
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</tbody>
</table>

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

#### Plowed Dirt

**DESCRIPTION:** 60’ x 60’ pad chisel plowed field dirt. Large frozen slumps roughly 6” in diameter.

<table>
<thead>
<tr>
<th>Vehicle Set-Up</th>
<th>Test Speed (mph)</th>
<th>Roll Steer Angle (degree)</th>
<th>No Roll Steer Angle (degree)</th>
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</thead>
<tbody>
<tr>
<td>Open Rear Differential</td>
<td>27.5</td>
<td>44</td>
<td>130</td>
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<tr>
<td>Locked Rear Differential</td>
<td>27.2</td>
<td>46</td>
<td>120</td>
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#### Grass Field

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

<table>
<thead>
<tr>
<th>Vehicle Set-Up</th>
<th>Test Speed (mph)</th>
<th>Roll Steer Angle (degree)</th>
<th>No Roll Steer Angle (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Rear Differential</td>
<td>27.2</td>
<td>48</td>
<td>110</td>
</tr>
<tr>
<td>Locked Rear Differential</td>
<td>27.2</td>
<td>51</td>
<td>110</td>
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</tbody>
</table>

#### Pavement

**DESCRIPTION:** Polaris asphalt test pad in Roseau, MN.

<table>
<thead>
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<th>Vehicle Set-Up</th>
<th>Test Speed (mph)</th>
<th>Roll Steer Angle (degree)</th>
<th>No Roll Steer Angle (degree)</th>
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</thead>
<tbody>
<tr>
<td>Open Rear Diff</td>
<td>30</td>
<td>150</td>
<td>145</td>
</tr>
<tr>
<td>Locked Rear Diff</td>
<td>30</td>
<td>170</td>
<td>165</td>
</tr>
<tr>
<td>*No Rear Bar Open Diff</td>
<td>30</td>
<td>185</td>
<td>180</td>
</tr>
<tr>
<td>*No Rear Bar Locked Diff</td>
<td>30</td>
<td>225</td>
<td>220</td>
</tr>
</tbody>
</table>

*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**
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
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
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