LOG OF MEETING
DIRECTORATE FOR ENGINEERING SCIENCES

SUBJECT: Recreational Off-Highway Vehicles (ROVs) – Meeting requested by the U.S. Consumer Product Safety Commission (CPSC) staff to discuss test methodology and test results of static and dynamic testing of ROVs by SEA Limited for CPSC staff and Carr Engineering Inc. (CEI) for the Recreation Off-Highway Vehicle Association (ROHVA).

DATE OF MEETING: July 19, 2012

PLACE OF MEETING: U.S. Consumer Product Safety Commission, Bethesda, MD

LOG ENTRY SOURCE: Caroleene Paul, ESME

COMMISSION ATTENDEES: See attached attendance list

NON-COMMISSION ATTENDEES: See attached attendance list

SUMMARY OF MEETING:

CPSC staff presented staff's motivation for testing recreational off-highway vehicles (ROVs), summarized the conclusions from the extensive testing performed by SEA Limited, and introduced Dr. Gary Heydinger to discuss the test methodologies, data, and results of the ROV test effort. Presentation is attached.

Dr. Gary Heydinger of SEA Limited presented the test methodologies used in performing static and dynamic tests of 10 different ROVs. The presentation included SEA's data quality checks and discussion of the results of the dynamic tests. SEA believes their laboratory and dynamic test results are both very accurate and very repeatable. Presentation attached.

Dr. Gary Heydinger presented a review of materials related to drop throttle J-turn tests presented to CPSC staff by the Recreational Off-Highway Vehicle Association (ROHVA) in November 2011. SEA's presentation stressed that the inability of Carr Engineering Inc. (CEI) to duplicate some of the testing results of SEA does not mean that the testing results of SEA are inaccurate or unrepeatable. It was noted that the equation (submitted by ROHVA to CPSC staff) that was used by CEI to calculate the ground plane lateral acceleration is incorrect and does not conform to the equation cited in ROHVA's voluntary standard, ANSI/ROHVA 1-2011, or to the National Highway Traffic Safety Administration (NHTSA) Final Rule on the New Car Assessment Program; Rollover Resistance. In particular, the submitted CEI equation does not use measured vertical acceleration in calculating ground plane lateral acceleration and, per SAE sign convention, the equation adds to the magnitude of lateral acceleration instead of subtracting. It was also noted that SEA was able to measure peak lateral acceleration at vehicle rollover in over 200 dynamic tests because the data plots for each test clearly show the peak acceleration. Conversely, the exemplar lateral acceleration plot presented by CEI (in November 2011) indicates a lateral acceleration that is physically impossible based on the static stability of the vehicle. SEA believes CEI's lack of adherence to exacting test methodologies and/or errors in processing data are the likely reason for the variation in test results between SEA and CEI. Presentation attached.

James Walker of CEI presented additional data on J-turn repeatability tests that were performed by CEI. CEI performed 15 J-turn test runs on the same vehicle and found variations in the peak lateral acceleration measured at vehicle rollover and variations in the steering wheel angle measured at vehicle rollover. CEI was also unable to find correlation between understeer gradient and lateral acceleration. CEI uses a body roll correction factor in calculating the ground plane lateral acceleration and the resultant equation differs from the equation cited in ANSI/ROHVA 1-2011 and in NHTSA's Final Rule on the New Car Assessment Program. CEI also uses a different sign convention for the body roll angle that is not consistent with the Society of Automotive Engineers (SAE) sign convention. CEI believes their method of calculating ground plane lateral acceleration is equivalent to the method used by NHTSA and is therefore appropriate. Presentation attached.

MEETING ATTENDANCE RECORD
ROHVA / CPSC Staff – July 19, 2012

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ROHVA / CPSC Staff – July 19, 2012

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CPSC Staff Meeting With
Recreational Off-Highway Vehicle Association
Dynamic and Static Testing
July 19, 2012

Introduction

Purpose: Communicate test methods and results used by CPSC staff to evaluate ROV vehicles

Agenda

- Participant introductions
- CPSC - Staff motivation for testing ROVs
- Dr. Gary Heydinger of SEA Limited
  - Test Methods and Results
- Q & A

Recreational Off-Highway Vehicles
Dynamic and Static Testing

CPSC Staff Initiated Dynamic and Static Tests to:

- Document, evaluate, and compare stability and handling of typical ROVs
- Support rulemaking
- Assess characteristics affecting rollover
  - Rollover is a significant incident factor
- Gather consistent facts
  - Dynamic characteristics
  - Static measures
- Compare alternative performance measures

Independent Testing Conducted By SEA Limited

Ten Market Representative Vehicles Evaluated*

- Dynamic Tests
  - Drop and Constant Throttle J-Turn
  - Constant Radius Circle
  - Slowly Increasing Steer
  - Sinusoidal Sweep Steering
  - Flick Steering Input
- Vehicle Inertial Measurement Facility (VIMF)
  - Center of Gravity (CG) Location
  - Pitch, Roll, and Yaw Moments of Inertia

* Five also tested at AberdeenTest Center (A, B, D, F, H)

Independent Testing Conducted By SEA Limited

- Direct Measurements
  - Track Width
  - Wheel Base
  - Weight Distribution
  - Ground Clearance
  - Steering Ratio
- Calculations
  - SSF
  - Kst
- Static Tilt Table Tests

Recreational Off-Highway Vehicles

Dynamic and Static Testing

Conclusions

- Dropt Throttle J-Turn is a reliable test to measure directly lateral acceleration at rollover threshold
  - Rollover thresholds, Ay, vary from 0.62g to 0.79g.
  - Rollover steering angles vary from 85 degrees to 210 degrees at 30 mph drop throttle.
  - All vehicles tested experienced untripped rollover.
- Constant Radius Circle Test is reliable test to measure vehicle steering characteristic
  - Five vehicles have sub-limit oversteer.
  - Sub-limit oversteer is correctable with suspension changes.

S-E-A, Ltd. Presentation to CPSC and ROVHA on Methodologies used to Generate Static (Laboratory) and Dynamic (Field Testing) Test Data and Summary of Test Results

Gary J. Heydinger, Ph.D., P.E.
Director Vehicle Dynamics Division

July 19, 2012

S-E-A
Scientific Expert Analysis

Objectives of CPSC Testing Program

- To obtain vehicle characteristic data that is **accurate and repeatable** using measurement and test methods that are proven and accepted in the academic and industrial communities.
- To document, study, and compare the dynamic performance characteristics of commonly available recreational off-highway vehicles (ROV's).

Objectives of This Presentation

- To present methodologies used by S-E-A to generate static (laboratory) and dynamic (field testing) test data
- To provide an overview and partial summary of test results obtained by S-E-A

S-E-A, Ltd. Reports to CPSC

Vehicle Characteristics Measurements Of Recreational Off-Highway Vehicles, April 2011

http://www.cpsc.gov/library/foia/foia11/os/rov.pdf

Vehicle Characteristics Measurements Of Recreational Off-Highway Vehicles – Additional Results for Vehicle J, August 2011

http://www.cpsc.gov/library/foia/foia11/os/rovj.pdf

Laboratory Testing

"This section describes the laboratory measurements made as well as computations made to compute various rollover resistance metrics and other vehicle characteristics. This section is divided into three parts, one covering the vehicle characteristics and metrics determined from Vehicle Inertia Measurement Facility (VIMF) testing, one covering the vehicle characteristics and metrics determined from tilt table testing, and one covering the other miscellaneous laboratory measurements made."

Vehicle Loading Conditions

1. Curb

Full fluids and with the vehicle manufacturer's specified tires and tire pressures

2. Operator

Occupant load used was equivalent to a 95th percentile adult male weighing nominally 213 lb.

3. Operator and Passenger

4. Operator, Passenger, and Cargo Bed Load (GVWR)

The Cargo Bed Load used was specified to be the lesser of the vehicle manufacturer's maximum cargo bed load or the load required to reach the vehicle manufacturer's Gross Vehicle Weight Rating (GVWR)

5. Operator, Instrumentation, and Outriggers

For Loading Condition #5, the vehicle's lateral, longitudinal, and vertical CG positions were made to closely match those of Loading Condition #3.

6. Operator, Instrumentation, Cargo & Outriggers (GVWR)

For Loading Condition #6, the vehicle's lateral, longitudinal, and vertical CG positions were made to closely match those of Loading Condition #4.

S-E-A Vehicle Inertia Measurement Facility (VIMF) Tests

- Vehicle Weight
- Vehicle Center-of-Gravity Position
  Longitudinal, Lateral and Vertical (CG Height) Positions
- Vehicle Pitch, Roll and Yaw Moment of Inertias
- Vehicle Roll/Yaw Product of Inertia

Based on detailed error analyses and supported by the results of actual repeat testing, the repeatability of VIMF center of gravity height measurements is within ±0.5% of the measured values.

VIMF Uses a Stable Pendulum Method to Determine CG Height

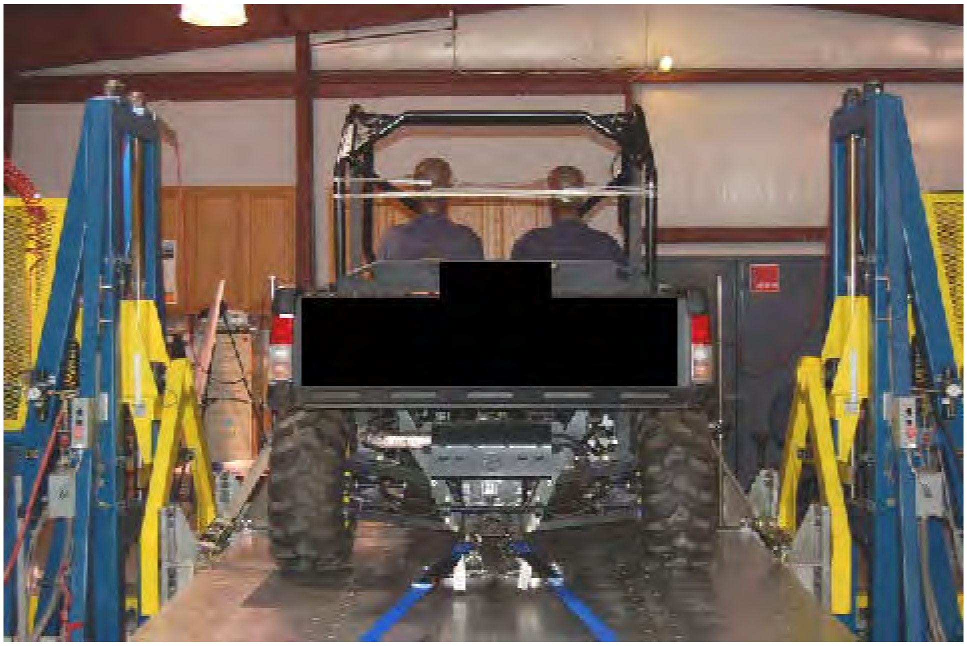
ISO 10392, Last Revised 2011
Road Vehicles – Determination of Centre of Gravity

Another Method is Axle Lift Method
(also Called Suspension (Lift) or Balance Angle Method)
SAE J874, Last Revised 1993
Earthmoving Machines - *Method for Locating the Center of Gravity*

Text from Scope of ISO 10392

"The axle lift method can generally provide centre-of-gravity height accuracy in the range of a few percent, while the stable pendulum method can provide accuracy in the range of 0.5%."

ROV on S-E-A
Vehicle Inertia Measurement Facility (VIMF)



Rollover Resistance Metrics
Based on Laboratory Measurements

Static Stability Factor (SSF)

Static Stability Factor (SSF) is given by:

$$SSF = \frac{T_{AVE}}{2 \times H_{CG}}$$

where T_{AVE} is the Average Track Width, and
H_{CG} is the Vehicle CG Height.

SSF is a fundamental rollover resistance metric which equals the lateral acceleration in g's at which rollover begins in the most simplified rollover analysis of a vehicle represented by a rigid body without suspension movement or tire deflections. NHTSA uses SSF, measured with vehicles loaded in a Driver Only configuration, to evaluate passenger vehicle rollover resistance for NCAP.

Rollover Resistance Metrics
Based on Laboratory Measurements

Lateral stability coefficient (KST)

Lateral stability coefficient (KST) is given by:

$$KST = \frac{L \times T_R + L_{CG} \times (T_F - T_R)}{2 \times L \times H_{CG}}$$

where L is the Vehicle Wheelbase,
T_F is the Front Track Width,
T_R is the Rear Track Width, and
L_{CG} is the Longitudinal Distance from the Rear Axle to the CG, and
H_{CG} is the Vehicle CG Height.

NOTE: If the front track width and rear track width of a vehicle are equal, then KST is equal to SSF.

Rollover Resistance Metrics
Based on Laboratory Measurements

Critical Sliding Velocity (CSV)

Critical Sliding Velocity (CSV) is given by:

$$CSV = \sqrt{\frac{2 \times g \times I_{oxx}}{M \times H_{CG}^2}\left(\sqrt{\frac{T_{AVE}^2}{4} + H_{CG}^2} - H_{CG}\right)}$$

where g is the Gravitational Constant,
M is the Vehicle Mass,
T_{AVE} is the Average Track Width,
H_{CG} is the Vehicle CG Height, and
I_{oxx} is the Effective Roll Moment of Inertia about the Tip Pivot, given by:

$$I_{oxx} = I_{xx} + M\left(\frac{T_{AVE}^2}{4} + H_{CG}^2\right)$$

where I_{xx} is the Vehicle Roll Moment of Inertia about its CG.

S-E-A Ltd. Tilt Table Tests

- Driver's side and passenger's side tilts were performed.
- S-E-A tilt table set-up provides for smooth tilting at rates as slow as 0.1 deg/sec.
- The S-E-A tilt table platform is very rigid, having deflections of less than 0.1 inch for a vehicle weight up to 10,000 lb. It is also very flat, with a flatness tolerance of +/- 0.1 inch.
- **Based on repeatability evaluations conducted using a range of different vehicles, S-E-A believes that the repeatability of the measurements of two-wheel lift is within +/- 0.1 degrees**.

Section from: ***ANSI/OPEI B71.9 - 2012***
American National Standard for Multipurpose Off-Highway Utility Vehicles

8.7 Tilt Table Stability

8.7.1.4 Required Tools, Instrumentation or Other Devices

a) A device to measure the angle of the test surface with an accuracy of ±0.5 degree (0.87% grade).

Rollover Resistance Metrics
Based on Laboratory Measurements

Tilt Table Angle (TTA) and Tilt Table Ratio (TTR)

Tilt Table Angle (TTA) is the angle at which two-wheel lift occurs.

Tilt Table Ratio (TTR) is given by:

$$\text{TTR} = tan\left(\text{TTA}\right)$$

ROV on S-E-A Tilt Table

Other Laboratory Measurements Made by S-E-A Ltd.

- Front and Rear Ground Clearance in the Operator and Passenger Loading Condition

- Steering Ratio in the Operator and Passenger Loading Condition
  - Linear curve fits of the measured data in the range of $\pm 180°$ of steering wheel angle were used to compute the overall steering ratios.

Vehicle A

	Curb	Operator	Operator & Passenger	Operator, Passenger & Cargo (GVWR)	Operator, Inst & Outriggers	Operator, Inst, Cargo & Outriggers (GVWR)
VIMF Test Number		4180	4181	4182	4183	4184
Total Vehicle Weight (lb)	1218.7	1431.7	1644.5	1998.4	1644.2	1998.8
Left Front Weight (lb)	259.8	317.5	343.9	334.5	357.3	341.6
Right Front Weight (lb)	278.7	309.4	371.6	357.2	352.2	350.9
Left Rear Weight (lb)	319.5	441.2	444.0	629.4	462.4	621.5
Right Rear Weight (lb)	360.7	363.6	485.0	677.3	472.3	684.8
Front Track Width (in)	45.20	45.20	45.40	45.25	45.40	45.25
Rear Track Width (in)	43.60	43.60	44.25	45.50	44.25	45.50
Average Track Width (in)	44.40	44.40	44.83	45.38	44.83	45.38
Wheelbase (in)	75.15	75.15	75.15	75.15	75.15	75.15
CG Longitudinal (in)	41.94	42.24	42.45	49.14	42.72	49.11
CG Lateral (in)	1.09	-1.33	0.94	0.80	0.07	0.82
CG Height (in)		24.56	25.52	25.35	25.26	
Roll Inertia - I_{XX} (ft-lb-s^2)		129	155	159	190	
Pitch Inertia - I_{YY} (ft-lb-s^2)		274	286	365	298	
Yaw Inertia - I_{ZZ} (ft-lb-s^2)		288	299	376	338	
Roll/Yaw - I_{XZ} (ft-lb-s^2)		9	15	24	12	
SSF		0.904	0.878	0.895	0.887	
KST		0.906	0.880	0.894	0.889	
CSV (mph)		7.32	7.17	7.17	7.47	
Tilt Table: Direction		Driver	Driver	Driver	Driver	
Tilt Table: First Wheel Lift		Rear	Rear	Rear	Rear	
Tilt Table Angle (deg)		33.0	32.8	32.7	32.7	
Tilt Table Ratio (TTR)		0.649	0.645	0.643	0.643	
Tilt Table: Direction		Passenger	Passenger	Passenger	Passenger	
Tilt Table: First Wheel Lift		Rear	Rear	Rear	Rear	
Tilt Table Angle (deg)		37.7	32.1	32.0	33.3	
Tilt Table Ratio (TTR)		0.773	0.626	0.626	0.658	
Average Tilt Table Angle (deg)		35.3	32.4	32.4	33.0	
Average Tilt Table Ratio (TTR)		0.711	0.635	0.635	0.650	
Front Ground Clearance (in)			8.60			
Rear Ground Clearance (in)			10.20			
Steering Ratio (deg/deg)			13.2			

Dynamic Testing

"This section describes the dynamic testing conducted at TRC between May 3 and October 12, 2010 (for Vehicles A through I) and on May 20, 2011 (for Vehicle J). The dynamic test evaluations included steering maneuvers on the flat dry asphalt surface of the Transportation Research Center's Vehicle Dynamics Area (VDA)."

S-E-A Designed and Fabricated CPSC Safety Outriggers

- S-E-A designed and built triangulated aluminum outriggers that extend on both sides on the tests vehicles.
- CPSC outriggers mount to the ROPS/OPS structures on the ROV's.
- The standard weight of these outriggers is 106 lb.
- The CG height of the CPSC outriggers is generally close to the test vehicle CG height.
- CPSC outriggers used for all vehicles except Vehicle F.
- For Vehicle F, a single titanium beam with nylon pucks at its ends was mounted securely to the top of the floorboard to serve as the safety outrigger.

Front View of ROV with CPSC Safety Outriggers

Side View of ROV with CPSC Safety Outriggers

TRC's Vehicle Dynamics Area (VDA)

- Asphalt
- 1% Slope – 0.6 degrees
- All vehicles tested in their most open driveline configuration

Table 1: TRC Skid Number Measurements

Location	VDA	
Pad #	V-5, dry	
Pavement	Asphalt	
Surface	Untreated	
Condition	Dry	
Date	Peak PBC	Slide SN
5/5/2010	92.5	82.2
6/1/2010	98.1	84.7
6/21/2010	92.3	85.0
7/5/2010	95.7	83.2
7/19/2010	97.0	82.8
8/2/2010	98.2	84.9
8/23/2010	93.3	83.5
9/7/2010	96.6	86.5
9/27/2010	94.6	86.3
5/11/2011	92.7	85.0

Section from: ***ANSI/OPEI B71.9 - 2012***
American National Standard for Multipurpose Off-Highway Utility Vehicles

7.5.2 Test Course for the Dynamic Stability Tests

a) The test course shall be a wide, horizontally flat surface sloping less than **1.0 degree (1.7% grade)**, …

b) The coefficient of friction for the dynamic stability test shall **be 0.8 ± 0.05**. A passing test using a surface with a coefficient of friction above **0.85** shall be allowed. Coefficient of friction shall be measured using the procedure found in ASTM E 1337-90 or another scientifically valid method that produces repeatable results comparable to ASTM E 1337-90.

8.5.4 Required Tools, Instrumentation or Other Devices

a) A device to measure the angle of the test surface with an accuracy of **±0.5 degree (0.87% grade)**.

Section from: ***ANSI/ROHVA 1 - 2011***
American National Standard for Multipurpose Off-Highway Utility Vehicles

8.3.1 Test Surface.

8.3.1.1 Test-Surface Preparation. Surface used for dynamic testing shall be constructed of asphalt or concrete having a **friction coefficient of at least 0.90** when measured in accordance with ASTM E 1337. The slope of this surface shall be no greater than **1 degree (1.7%)**.

S-E-A Vehicle Loading: Weights of Driver and Test Equipment

Table 2: Weights of Driver and Test Equipment	
Object	**Weight (lb)**
Test Driver with Helmet	182
ASC Handwheel Unit	34
ASC Battery Box	27
ASC Electronics Box and Cables	25
SEA Data Acquisition Computer	10
Auxiliary 12V Battery	25
RT3002 GPS/IMU, Antenna, and Cables	10
SEA Power Distribution Box and Misc. Straps	7
CPSC Triangulated Aluminum Safety Outriggers	106
Total Nominal Weight	**426**

S-E-A Vehicle Loading: Weights for GVWR Conditions

Table 3: Weight Difference Between Representative Operator and Passenger and GVWR Loading	
Vehicle	**Weight Difference (lb)**
A	355
B	274
C	487
D	983
E	496
F	601
G	911
H	357
I	458

Vehicle J tested in only the Representative Operator and Passenger Loading Condition

S-E-A Instrumentation

Table 4: Instrumentation Used During Dynamic Testing			
Transducer	**Measurement**	**Range**	**Accuracy or Linearity**
Oxford Technical Solutions RT3002 Inertial and GPS Navigation System	Longitudinal, Lateral, and Vertical Accelerations	$\pm$ 10 g	0.1% 1σ
	Roll, Pitch, and Yaw Rates	$\pm$ 100 deg/s	0.1% 1σ
	Speed	No Limit Specified	0.2% 1σ
	Roll and Pitch Angles	No Limit Specified	0.03° 1σ
	Vehicle Heading and Sideslip Angle	No Limit Specified	0.1° 1σ
Encoder on SEA, Ltd. ASC	Steering Wheel Angle	$\pm$ 800 deg	$\pm$ 0.25 deg

RT3002 Inertial and GPS Navigation System (Red Box) Mounted on a ROV

Automated Steering Controller (ASC) Mounted on a ROV

Translating Measured Accelerations to Vehicle CG Location

- When using a multi-axis inertial sensing system that measures linear accelerations and roll, pitch, and yaw angular rates, the position of the sensor must be accurately measured relative to the CG of the vehicle. These data are required to translate the acceleration quantities measured at the sensor location to those that occur at the actual vehicle CG, in order to remove roll, pitch and yaw effects.
- The equations on the following slide can be used to translate the acceleration data. The equations are derived from equations of general relative acceleration for a translating reference frame and they use the SAE convention for a Vehicle Dynamics Coordinate System.
- Upon entering the displacement information from the sensor location to the vehicle CG, the acceleration sensor used by S-E-A provides for a direct measurement of the accelerations at the CG of the vehicle.

See equations on following slide and reference:

***Consumer Information; New Car Assessment Program; Rollover Resistance; Final Rule**,*
Federal Register, Part II, Department of Transportation, NHTSA, Pg. 59274, October 14, 2003.

Equation for Translating Measured Accelerations to Vehicle CG Location

$$x''_{corrected} = x''_{accel} - \left(\Theta'^2 + \Psi'^2\right)x_{disp} + \left(\Theta'\Phi' - \Psi''\right)y_{disp} + \left(\Psi'\Phi' + \Theta''\right)z_{disp}$$

$$y''_{corrected} = y''_{accel} - \left(\Theta'\Phi' + \Psi''\right)x_{disp} - \left(\Phi'^2 + \Psi'^2\right)y_{disp} + \left(\Psi'\Theta' - \Phi''\right)z_{disp}$$

$$z''_{corrected} = z''_{accel} + \left(\Psi'\Phi' - \Theta''\right)x_{disp} + \left(\Psi'\Theta' + \Phi''\right)y_{disp} - \left(\Phi'^2 + \Theta'^2\right)z_{disp}$$

where:

$x''_{corrected}$, $y''_{corrected}$, and $z''_{corrected}$ = longitudinal, lateral, and vertical accelerations, respectively, at the vehicle's CG

x''_{accel}, y''_{accel}, and z''_{accel} = longitudinal, lateral, and vertical accelerations, respectively, at the accelerometer location

x_{disp}, y_{disp}, and z_{disp} = longitudinal, lateral, and vertical displacements, respectively, of the CG with respect to the accelerometer location

φ' and φ'' = roll rate and roll acceleration, respectively

Θ' and Θ'' = pitch rate and pitch acceleration, respectively

Ψ' and Ψ'' = yaw rate and yaw acceleration, respectively

***Consumer Information; New Car Assessment Program; Rollover Resistance; Final Rule**,*
Federal Register, Part II, Department of Transportation, NHTSA, Pg. 59274, October 14, 2003.

Equation for Planar Ground Plane (Corrected) Lateral Acceleration

Accelerometers rigidly mounted in vehicles sense accelerations in a vehicle-body-fixed coordinated system. Ground plane (or so-called "Corrected") lateral acceleration can be computed from the measured vehicle-body-fixed lateral acceleration and the vehicle-body-fixed vertical acceleration (both of which sense accelerations caused by the maneuver and by gravity). The ground plane (Corrected) lateral acceleration is the acceleration parallel to the road plane, and it is computed as (using SAE vehicle coordinate sign conventions):

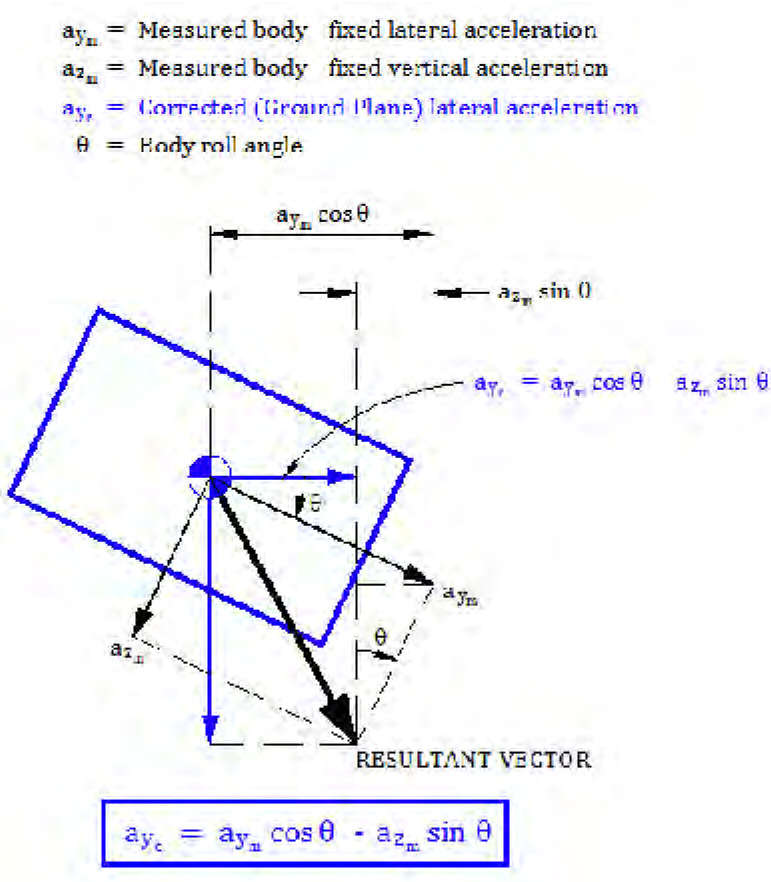
$$Corrected\ Ay = Measured\ Ay \times \cos(\phi) - Measured\ Az \times \sin(\phi)$$

$$where\ \phi = body\ roll\ angle$$

See derivation on following slide and two references:

Consumer Information; New Car Assessment Program; Rollover Resistance; Final Rule, *Federal Register, Part II, Department of Transportation, NHTSA, Pg. 59274, October 14, 2003.*

American National Standard for Recreational Off-Highway Vehicles
ANSI/ROHVA 1 – 2011, 2011



S-E-A Data Processing

- All data channels sampled at 100 Hz (100 samples per second)
- Details on digital filters used as part of processing the data channels are listed in the April 2011 S-E-A report.
- Details on any calculations used to generate graphs and curve fits of measured data are listed in the April 2011 S-E-A report.

S-E-A Lateral Acceleration Measurements

- S-E-A used a sensor that provides for a direct measurement of ground plane lateral acceleration (sometimes referred to as Corrected Ay).
- S-E-A's sensor was also configured to provide ground plane lateral acceleration at the measured center of gravity of each vehicle.

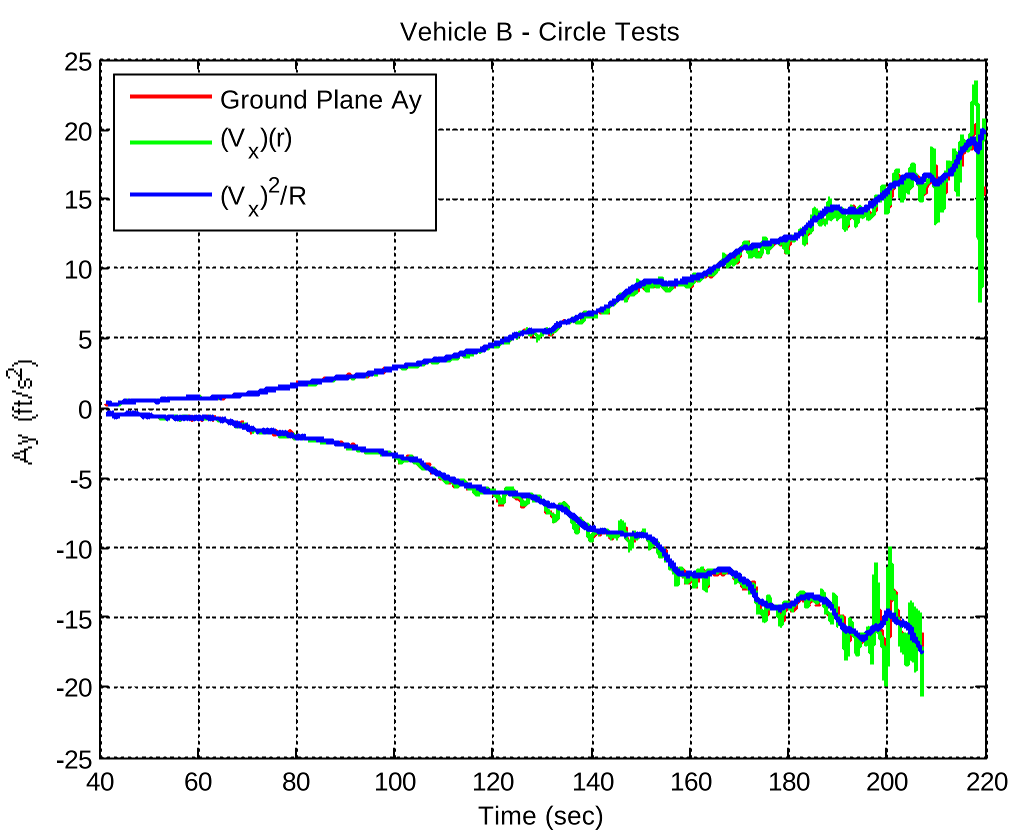
S-E-A Data Quality Checks

During SAE J266 constant radius circle tests the following fundamental relationships involving ground plane lateral acceleration (Ay), vehicle longitudinal speed (Vx), yaw rate (r), and circle radius (R) hold true:

$$Ground\ \ Plane\,(\,Corrected\,)\ Ay = V_x \times r = \frac{V_x^{\ 2}}{R}$$

The graph on the following slide contains data measured by S-E-A during the circle tests for Vehicle B in the representative Operator plus Passenger loading condition. The plots indicate that the S-E-A data is consistent with these fundamental relationships.

S-E-A performed similar data quality checks for all vehicles tested for and reported to CPSC, and confirmed that the quality of this data for all vehicles tested was similar to that shown on the following page. The data channels used for ground plane Ay, Vx and r during these tests are the same data channels S-E-A used for all tests, including the dropped throttle J-turn tests.



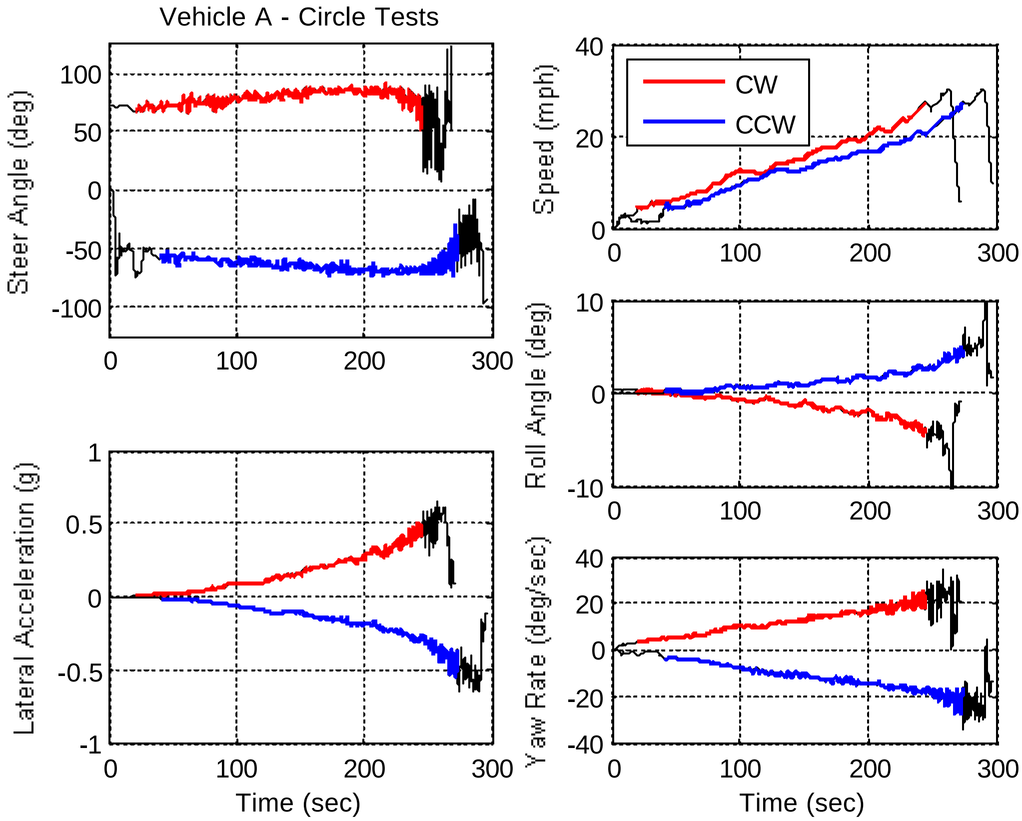
Dynamic Tests Conducted by S-E-A

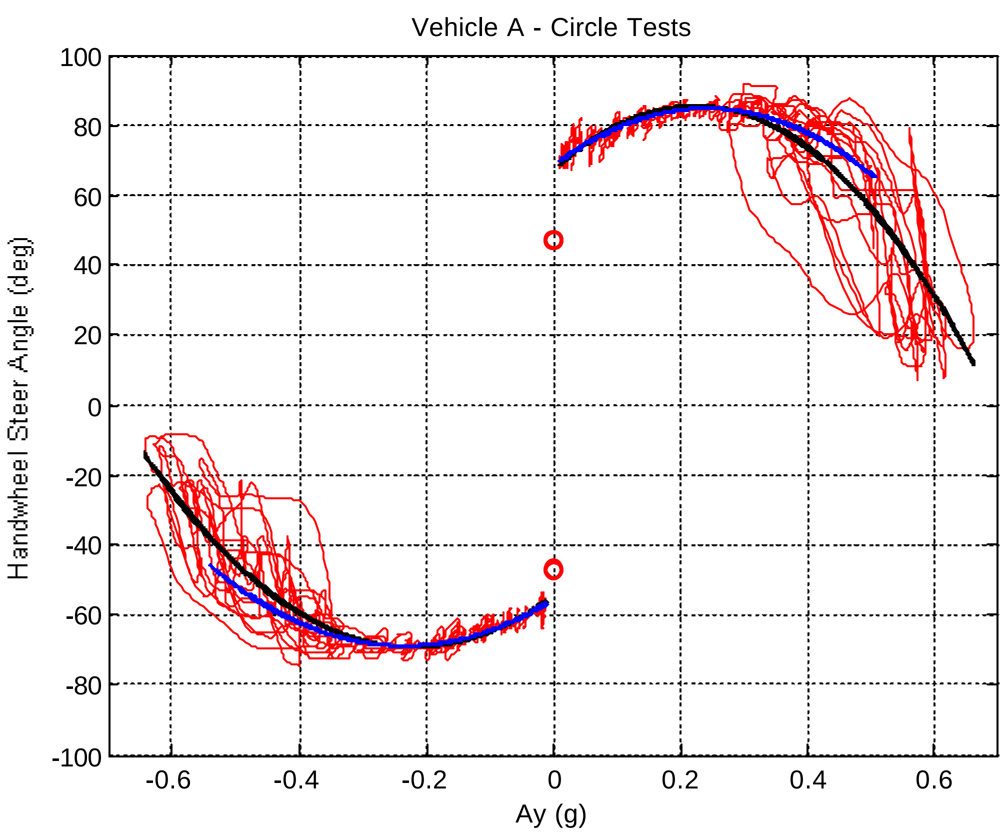
- Constant Radius (100 ft) Circle Tests
- Constant Speed (30 mph) Slowly Increasing Steer Tests
- Dropped Throttle J-Turn (Step Steer) Tests (Initial Speed of 30 mph)
- Constant Throttle J-Turn (Step Steer) Tests (Initial Speed of 30 mph)
- Sinusoidal Sweep Steering (Frequency Response) Tests (20 mph)
- Constant Speed (30 mph) Steering Flick Tests
- Maximum Speed Tests

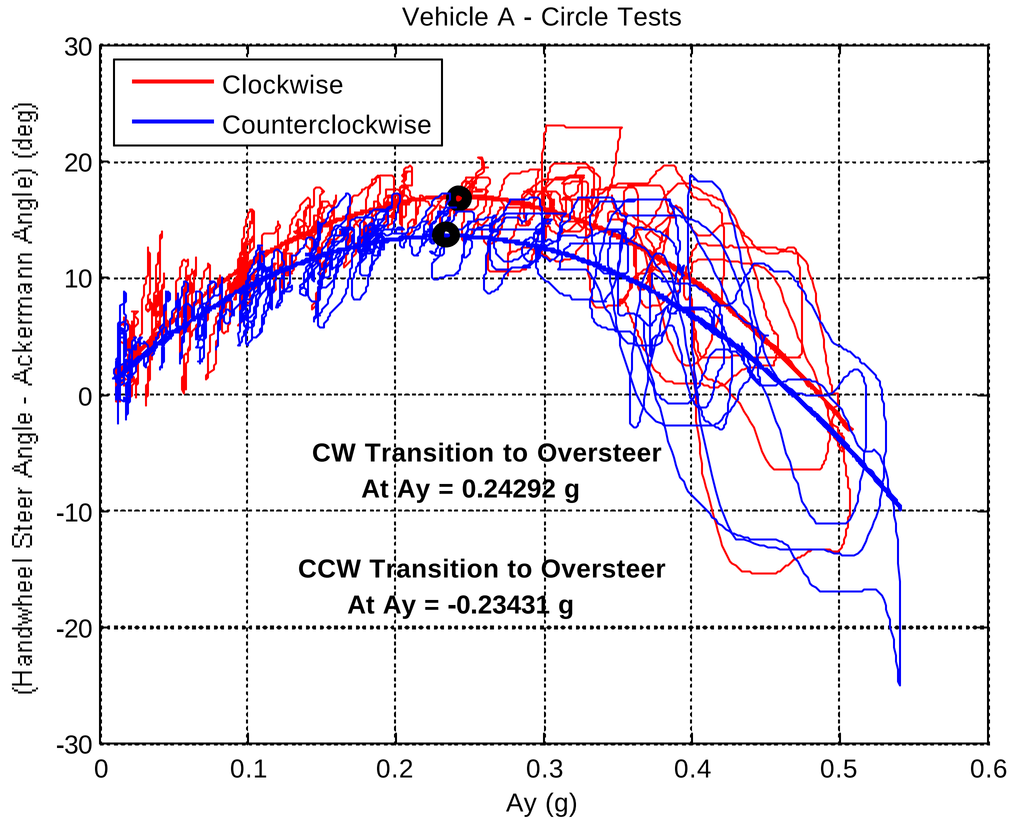
Over 900 Dynamic Tests Were Performed

Constant Radius (100 ft) Circle Tests

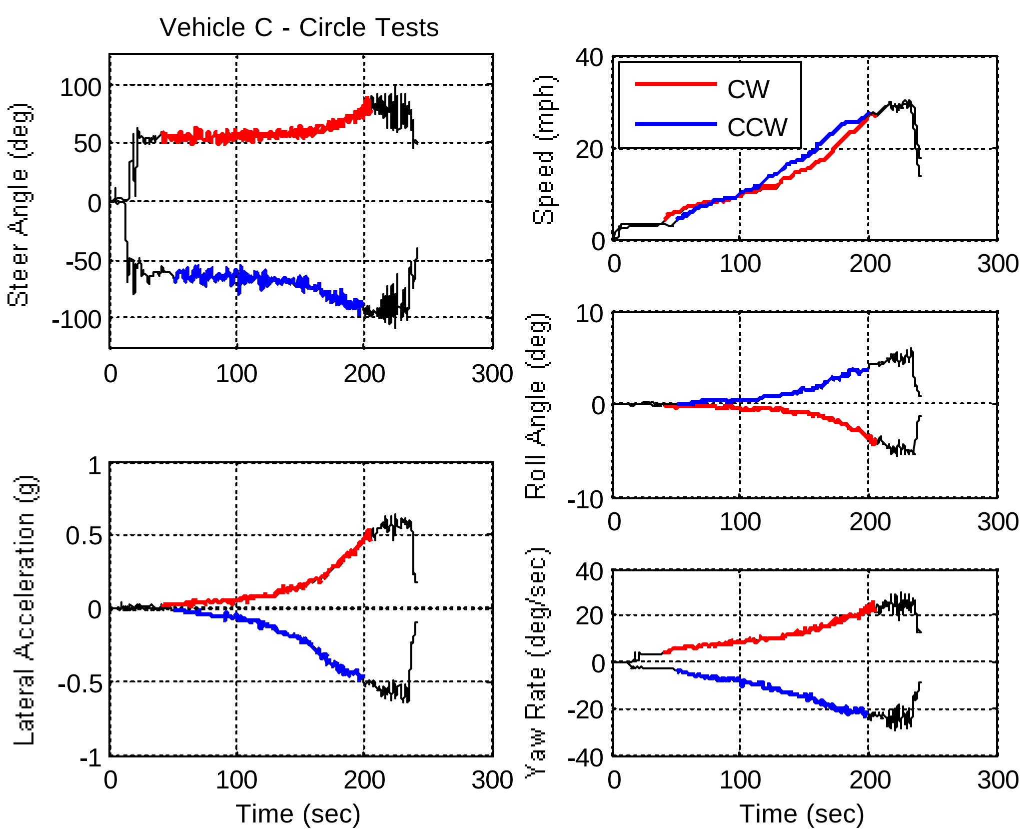
- Tests Conducted in both Clockwise (CW) and Counterclockwise (CCW) Directions
- Tests Conducted in Accordance with: *SAE Surface Vehicle Recommended Practice - Steady-State Directional Control Test Procedures For Passenger Cars and Light Trucks, SAE J266, 1996.*
- Detailed results from the circle tests are contained in Appendix C of the S-E-A reports.


Vehicle A - Circle Tests
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

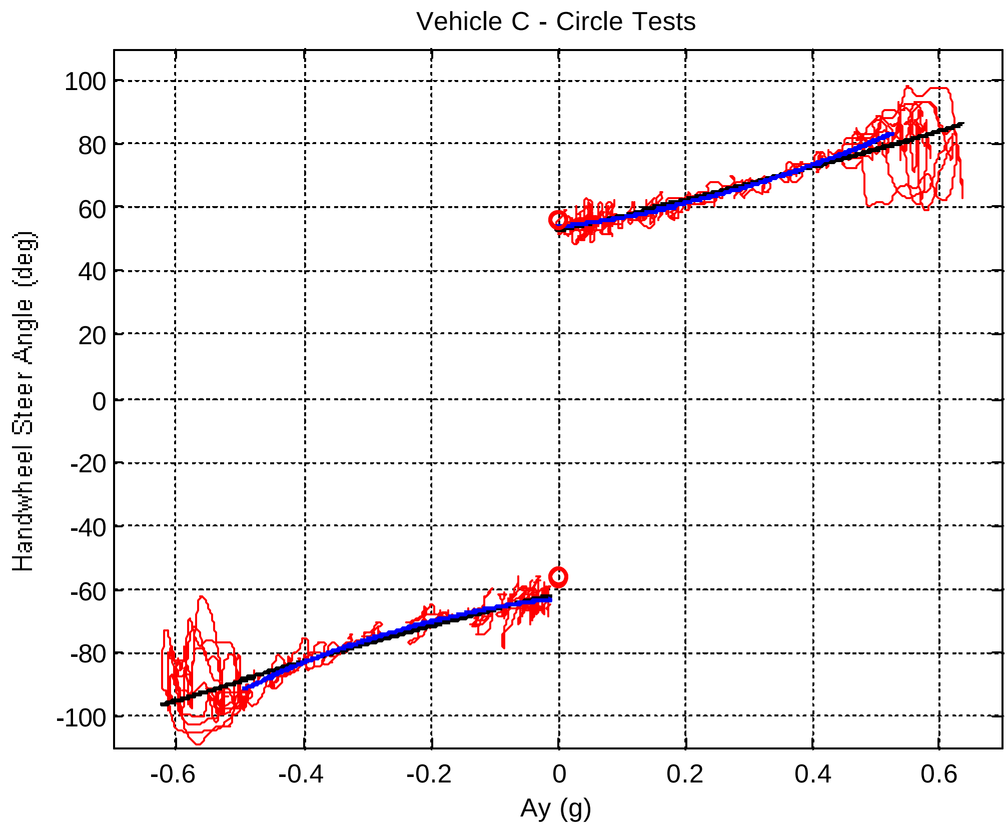

Vehicle A - Circle Tests
Handwheel Steer Angle (deg)
Ay (g)

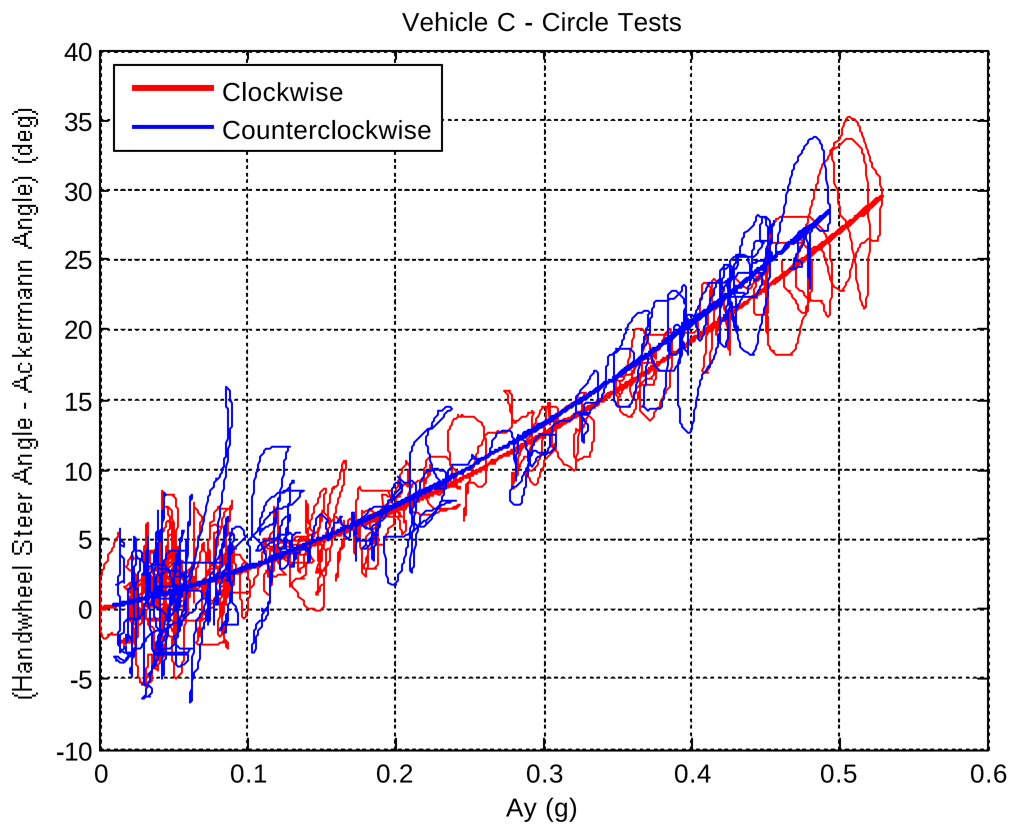

Vehicle A - Circle Tests
Clockwise
Counterclockwise
CW Transition to Oversteer
At Ay = 0.24292 g
CCW Transition to Oversteer
At Ay = -0.23431 g
(Handwheel Steer Angle - Ackermann Angle) (deg)
Ay (g)
30
20
10
0
-10
-20
-30
0
0.1
0.2
0.3
0.4
0.5
0.6

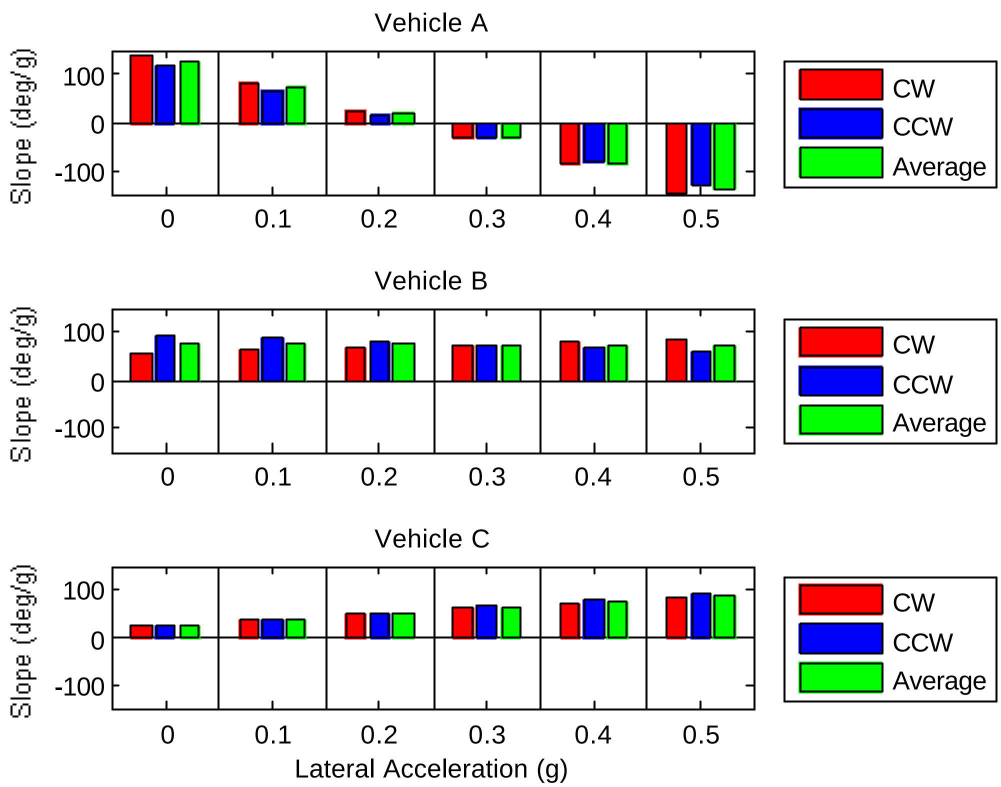
41


Vehicle C - Circle Tests
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

42

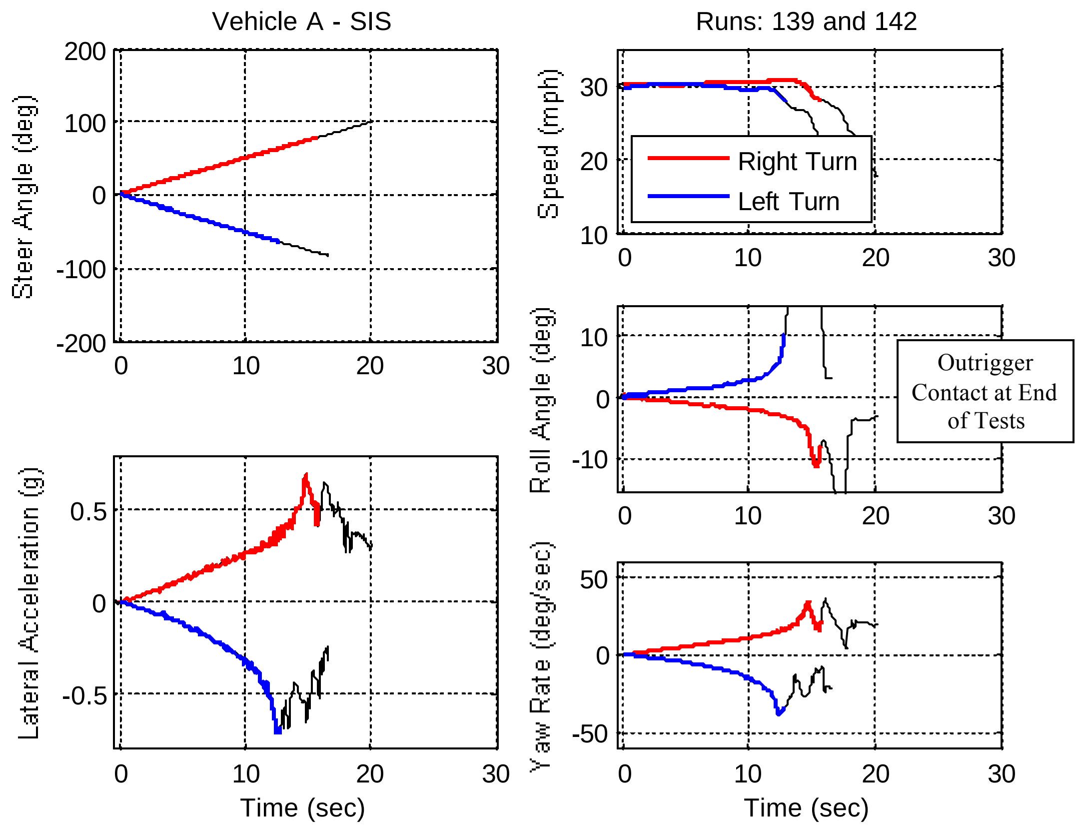

Vehicle C - Circle Tests
Handwheel Steer Angle (deg)
100
80
60
40
20
0
-20
-40
-60
-80
-100
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
Ay (g)


Vehicle C - Circle Tests
Clockwise
Counterclockwise
(Handwheel Steer Angle - Ackermann Angle) (deg)
40
35
30
25
20
15
10
5
0
-5
-10
0
0.1
0.2
0.3
0.4
0.5
0.6
Ay (g)



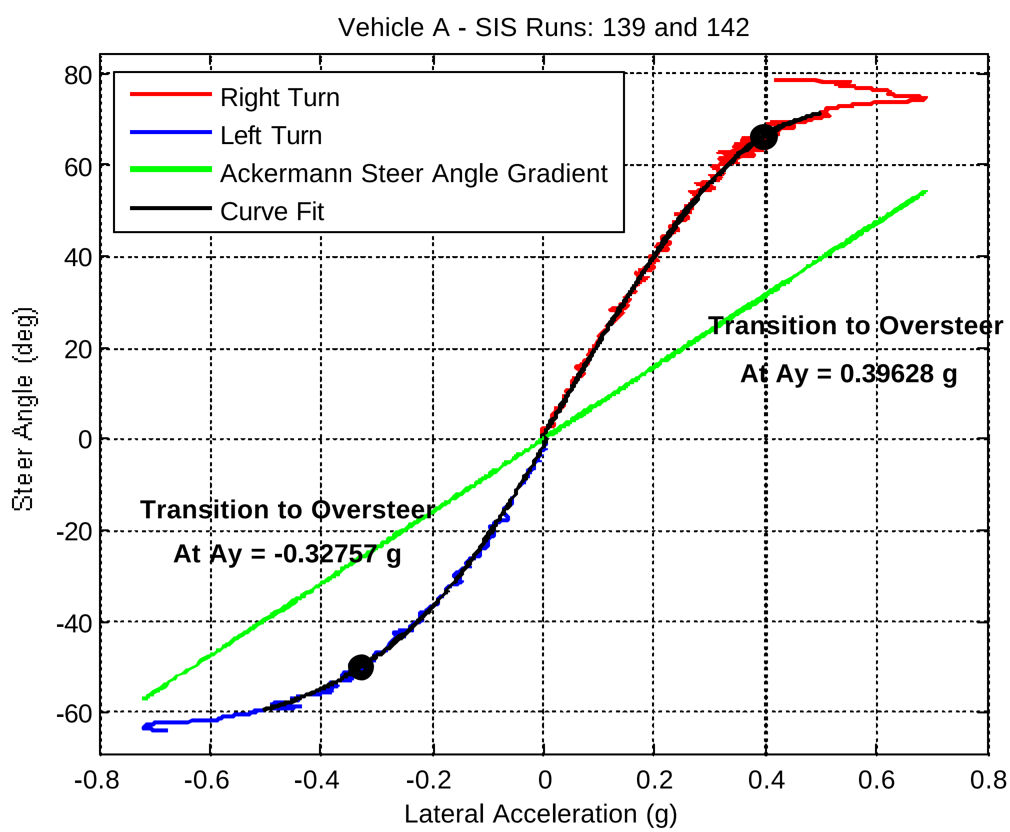
Constant Speed (30 mph) Slowly Increasing Steer Tests

- Tests Conducted in both Clockwise (CW) and Counterclockwise (CCW) Directions
- Tests Conducted in Accordance with: *SAE Surface Vehicle Recommended Practice - Steady-State Directional Control Test Procedures For Passenger Cars and Light Trucks, SAE J266, 1996.*
- Detailed results from the slowly increasing steer tests are contained in Appendix D of the S-E-A reports.



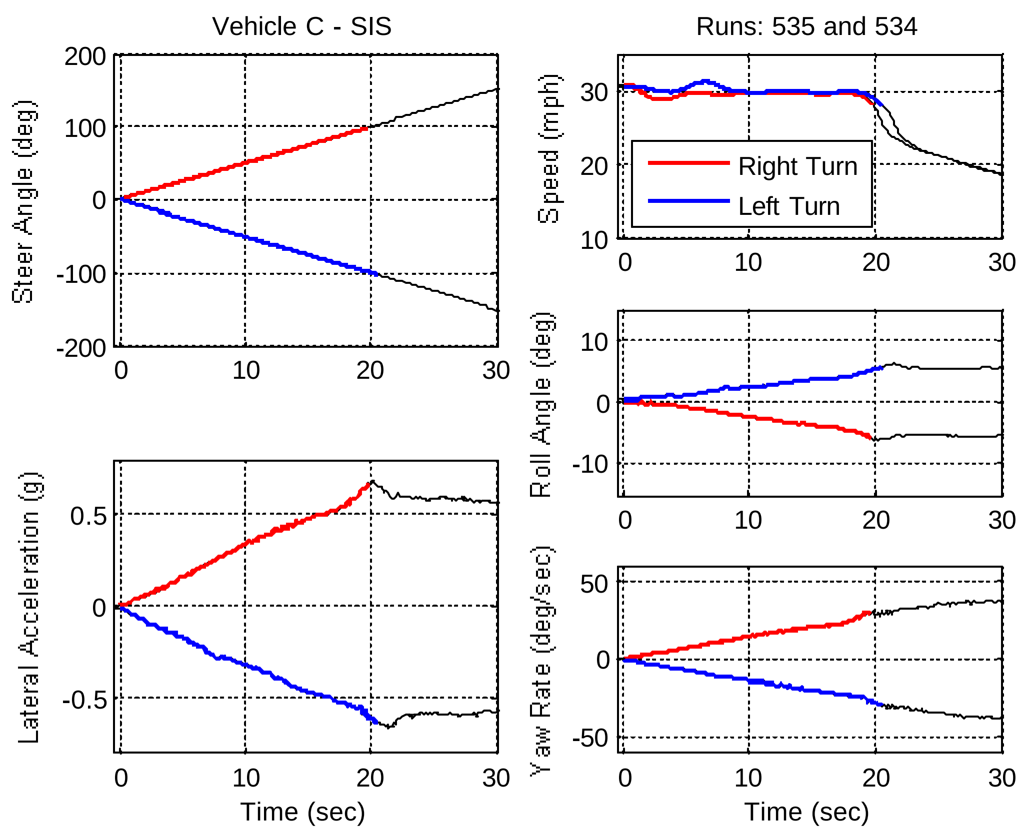
Vehicle A - SIS
Runs: 139 and 142
Steer Angle (deg)
Lateral Acceleration (g)
Speed (mph)
Roll Angle (deg)
Yaw Rate (deg/sec)
Time (sec)
Right Turn
Left Turn
Outrigger Contact at End of Tests

47

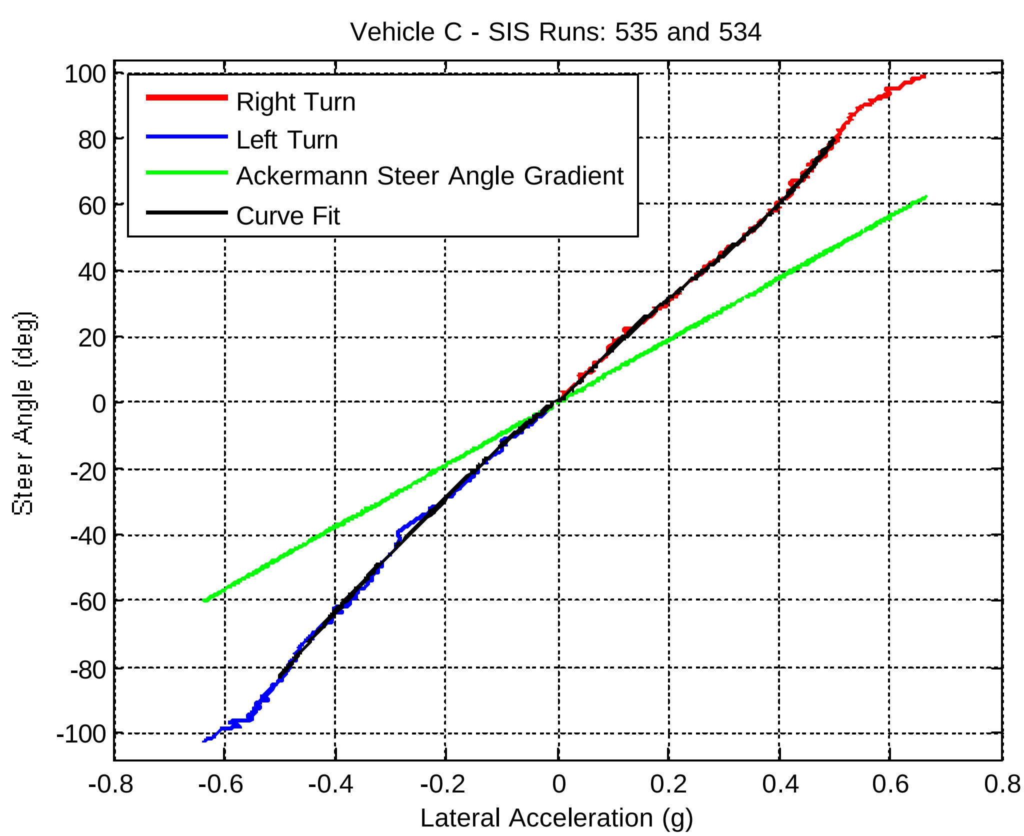


Vehicle A - SIS Runs: 139 and 142
Right Turn
Left Turn
Ackermann Steer Angle Gradient
Curve Fit
Transition to Oversteer
At Ay = 0.39628 g
Transition to Oversteer
At Ay = -0.32757 g
Steer Angle (deg)
Lateral Acceleration (g)

48



Vehicle C - SIS
Runs: 535 and 534
Steer Angle (deg)
Speed (mph)
Right Turn
Left Turn
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)



Vehicle C - SIS Runs: 535 and 534
Right Turn
Left Turn
Ackermann Steer Angle Gradient
Curve Fit
Steer Angle (deg)
Lateral Acceleration (g)

Dropped Throttle J-Turn (Step Steer) Tests (Initial Speed of 30 mph)

- Tests Conducted in both Right and Left Turn Directions
- For the dropped throttle J-turn tests, the test driver drove each vehicle along a straight-line path at a speed slightly above 30 mph. He then dropped the throttle and triggered the ASC to initiate the steering input precisely when the vehicle speed reached 30 mph. The speed of 30 mph was used because it was believed that at this speed all of the vehicles tested, in both loading configurations, would result in a tip-up condition given high enough steering magnitudes. This was the case for all of the vehicles tested.
- The steering rate used for all of the J-turn tests was 500 deg/sec.

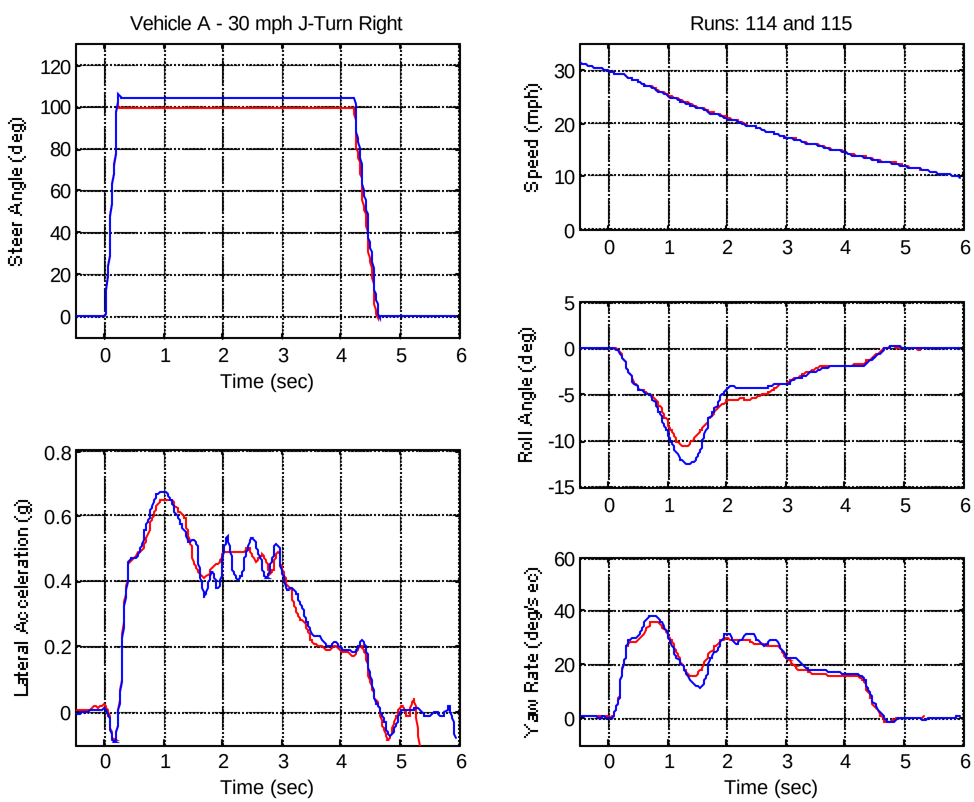
Dropped Throttle J-Turn (Step Steer) Tests (Initial Speed of 30 mph)

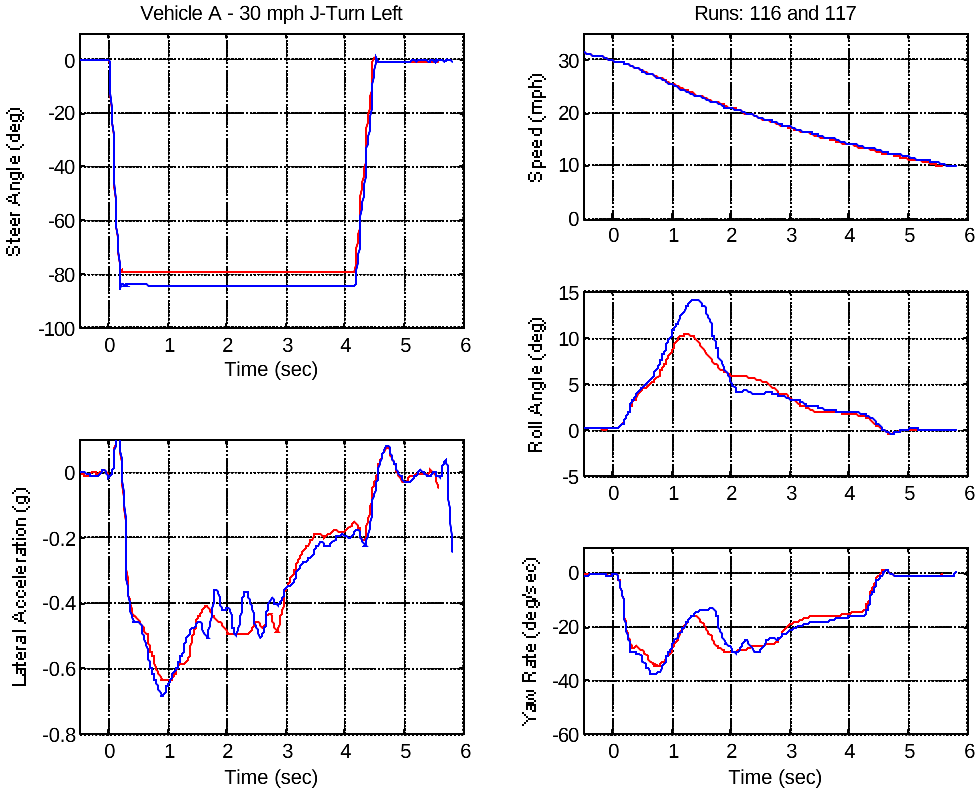
- The magnitudes of the steering inputs were varied to identify the minimum steering magnitude required to result in tip-up in the 30 mph dropped throttle tests. For this testing, tip-up events are considered those that produced significant two-wheel lift and in almost all cases outrigger contact. These tests provided a measure of the minimum lateral accelerations and minimum steering wheel angles required to cause two-wheel lifts during the tests.

Dropped Throttle J-Turn (Step Steer) Tests (Initial Speed of 30 mph)

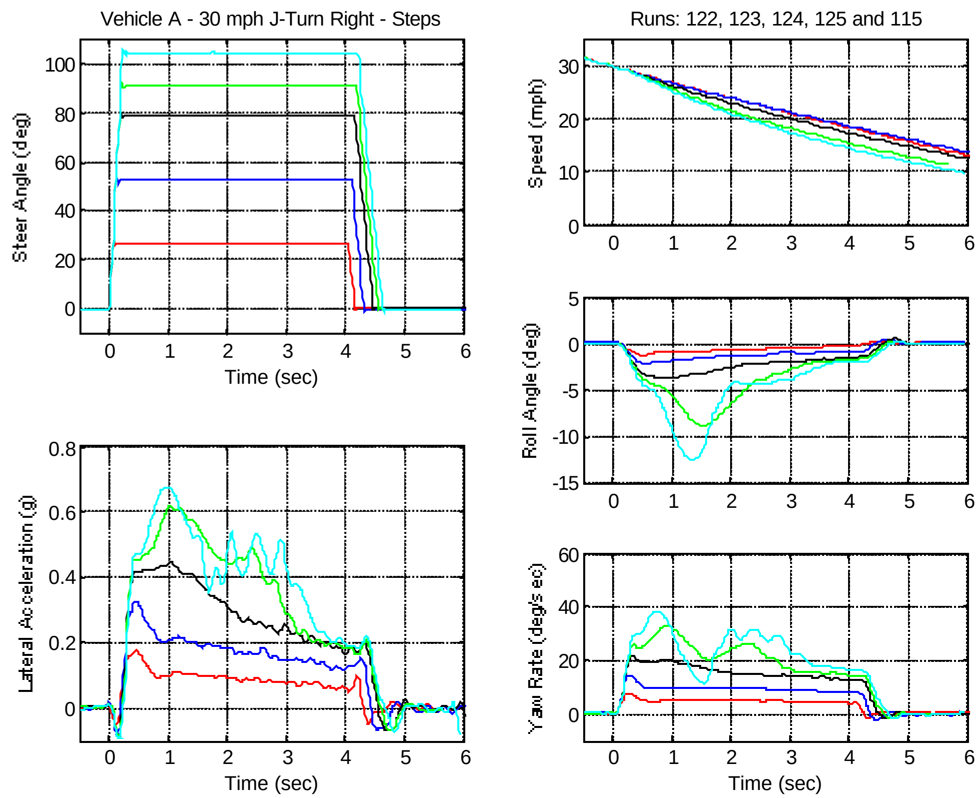
- After identifying the minimum steering wheel magnitudes required for tip-ups in the dropped throttle J-turn tests, a series of four additional dropped throttle tests were conducted, using steering magnitudes of 25%, 50%, 75%, and 87.5% of the tip-up producing steering magnitudes. These additional tests using steps in the steering magnitudes were conducted to evaluate the vehicles' responses in J-turns at various maneuver severities, and to evaluate if lateral acceleration to steering input gains could be related to vehicle understeer/oversteer behavior.

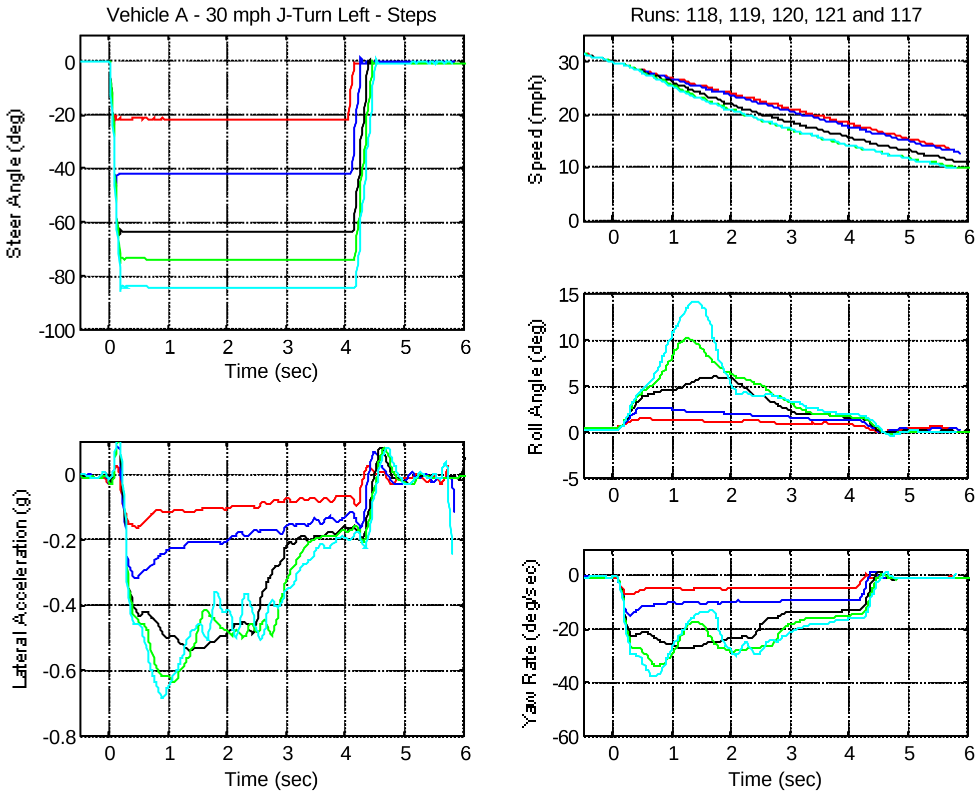
- Detailed results from the dropped throttle J-turn tests are contained in Appendix F of the S-E-A reports.



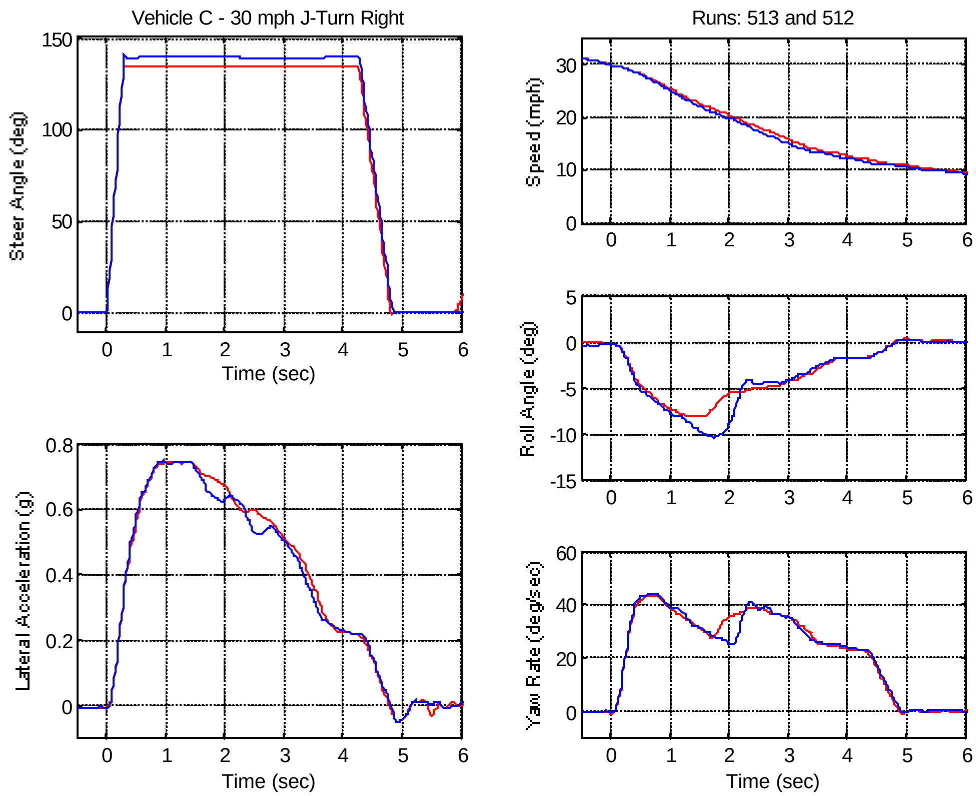

Vehicle A - 30 mph J-Turn Left
Runs: 116 and 117
Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)

55

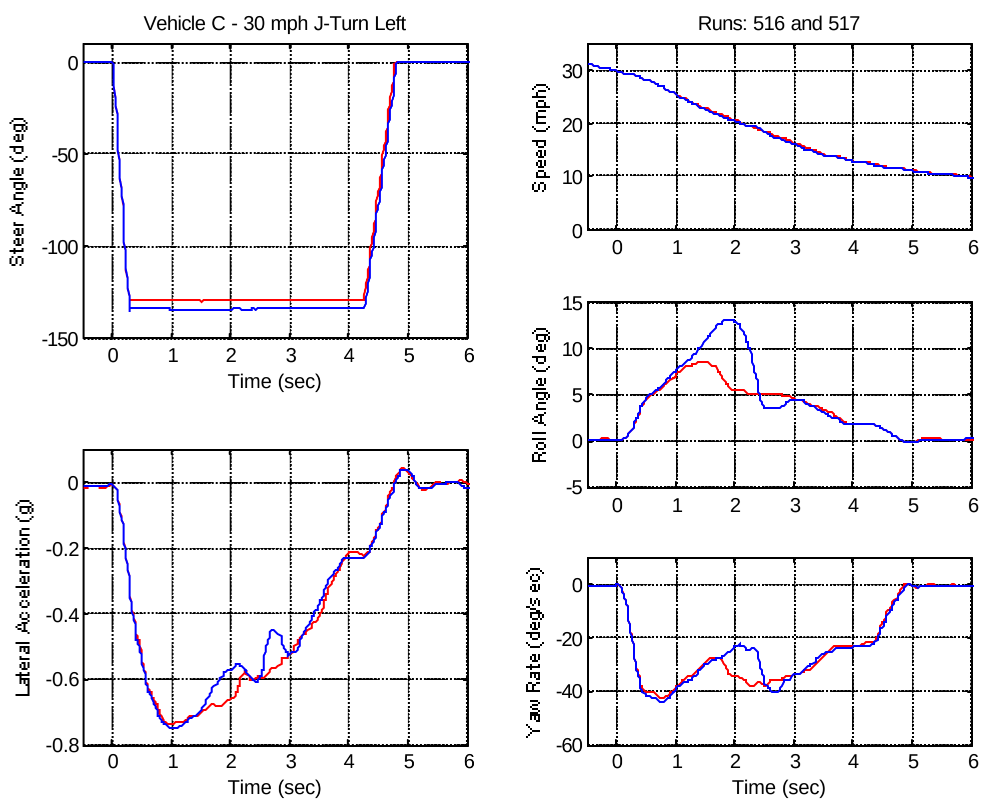

Vehicle A - 30 mph J-Turn Right - Steps
Runs: 122, 123, 124, 125 and 115
Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)



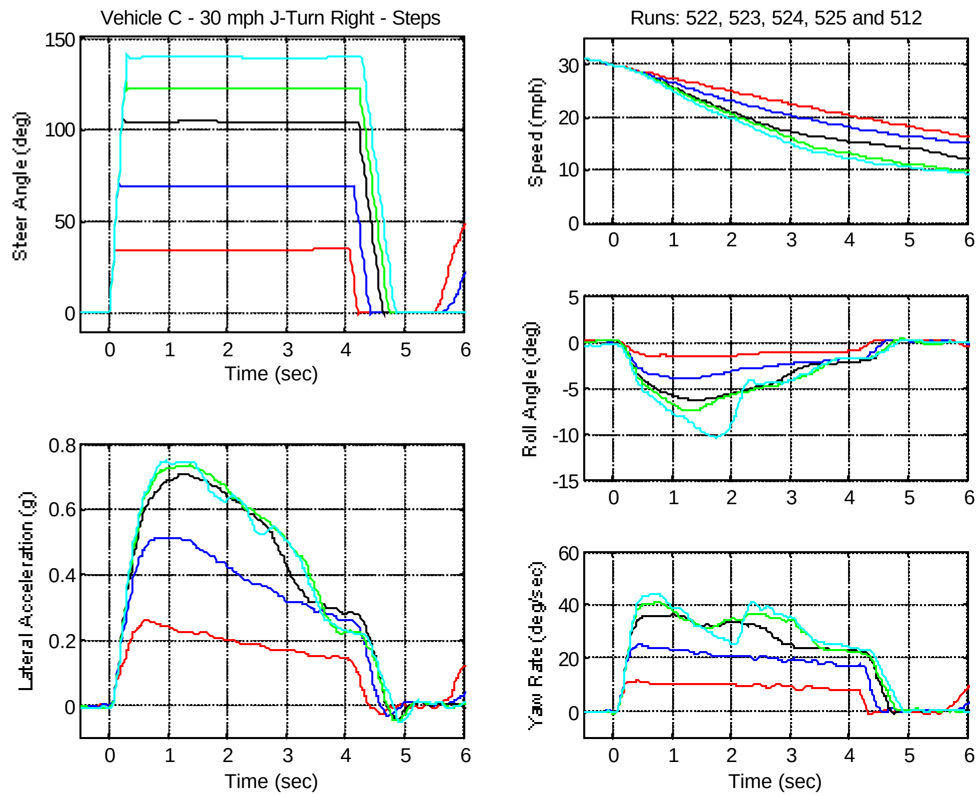
Maximum Lateral Accelerations During Dropped Throttle J-Turns Vehicle A – Operator and Passenger Loading						
	Right Steer Maneuvers		**Left Steer Maneuvers**		**Average of Right and Left Maneuvers**	
Percentage of Steering Required for Two Wheel Lift (%)	**Steering Angle (deg)**	**Lateral Accel. (g)**	**Steering Angle (deg)**	**Lateral Accel. (g)**	**Steering Angle (deg)**	**Lateral Accel. (g)**
0.0	0.0	0.00	0.0	0.00	0.0	0.000
25.0	26.3	0.17	-21.3	-0.16	23.8	0.165
50.0	52.5	0.32	-42.5	-0.31	47.5	0.315
75.0	78.8	0.44	-63.8	-0.53	71.3	0.485
87.5	91.9	0.61	-74.4	-0.63	83.1	0.620
100.0	105.0	0.67	-85.0	-0.67	95.0	0.670


Vehicle C - 30 mph J-Turn Right
Runs: 513 and 512
Steer Angle (deg)
Time (sec)
Lateral Acceleration (g)
Speed (mph)
Roll Angle (deg)
Yaw Rate (deg/sec)

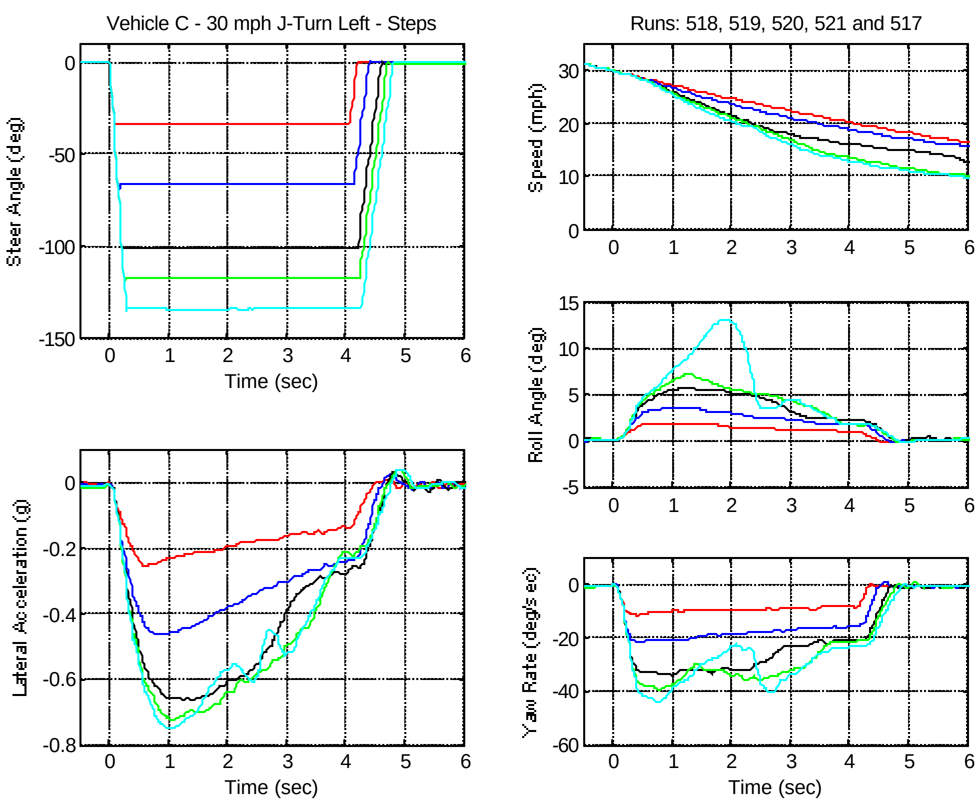
59


Vehicle C - 30 mph J-Turn Left
Runs: 516 and 517
Steer Angle (deg)
Time (sec)
Lateral Acceleration (g)
Speed (mph)
Roll Angle (deg)
Yaw Rate (deg/sec)

60


Vehicle C - 30 mph J-Turn Right - Steps
Runs: 522, 523, 524, 525 and 512
Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)

61

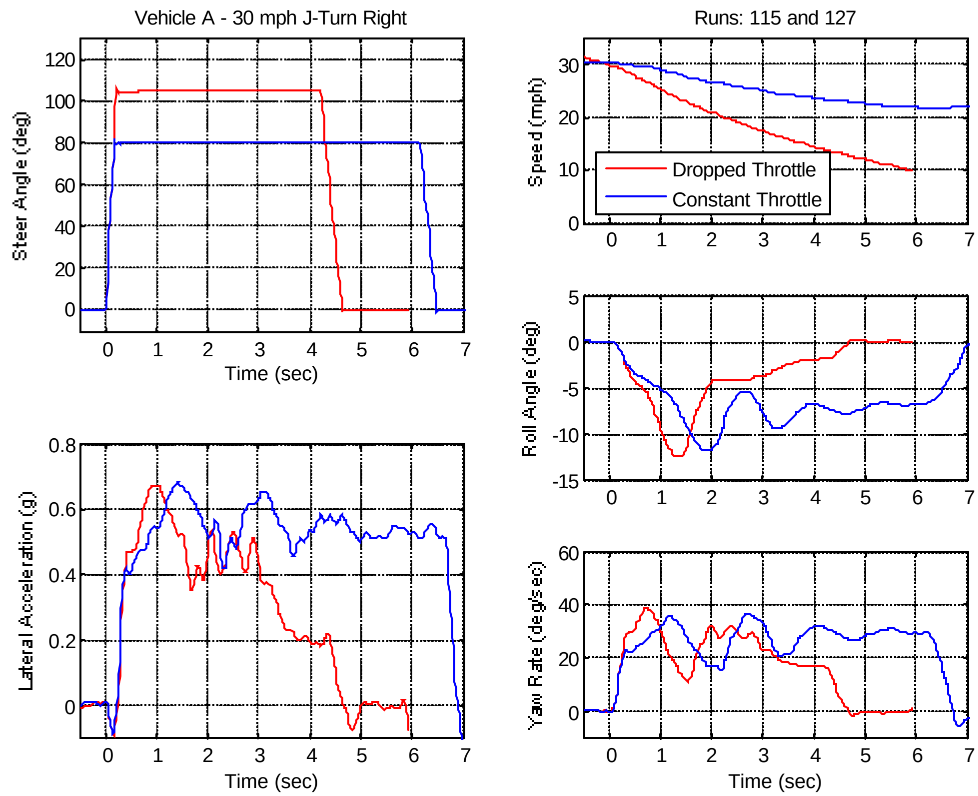

Vehicle C - 30 mph J-Turn Left - Steps
Runs: 518, 519, 520, 521 and 517
Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)

62

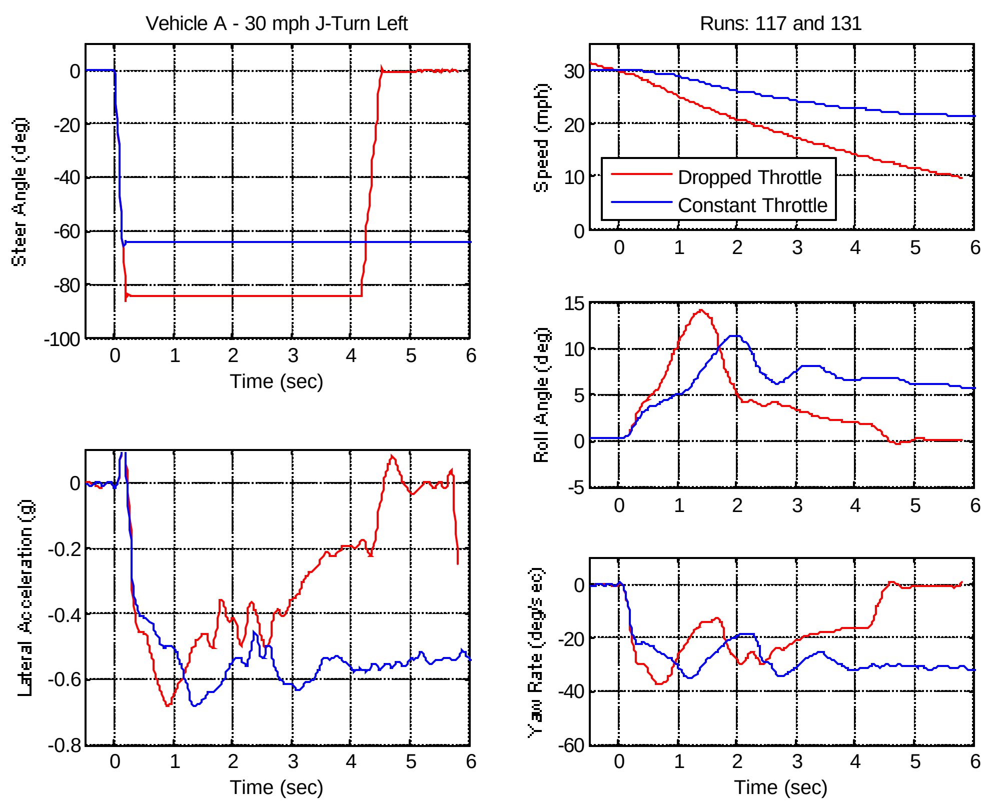
Maximum Lateral Accelerations During Dropped Throttle J-Turns Vehicle C – Operator and Passenger Loading						
	Right Steer Maneuvers		Left Steer Maneuvers		Average of Right and Left Maneuvers	
Percentage of Steering Required for Two Wheel Lift (%)	Steering Angle (deg)	Lateral Accel. (g)	Steering Angle (deg)	Lateral Accel. (g)	Steering Angle (deg)	Lateral Accel. (g)
0.0	0.0	0.00	0.0	0.00	0.0	0.000
25.0	35.0	0.25	-33.8	-0.25	34.4	0.250
50.0	70.0	0.51	-67.5	-0.46	68.8	0.485
75.0	105.0	0.70	-101.3	-0.66	103.1	0.680
87.5	122.5	0.73	-118.1	-0.72	120.3	0.725
100.0	140.0	0.74	-135.0	-0.74	137.5	0.740

Constant Throttle J-Turn (Step Steer) Tests (Initial Speed of 30 mph)

- Tests Conducted in both Right and Left Turn Directions
- For the constant throttle J-turn tests, the test driver drove each vehicle along a straight-line path at a nominal speed of 30 mph. While holding the throttle (gas pedal) constant, he triggered the ASC to initiate the steering input. The steering rates used for the constant throttle J-turn tests were 500 deg/sec. The magnitudes of the steering inputs were varied to identify the minimum steering magnitude required to result in tip-up.
- Detailed results from the constant throttle J-turn tests are contained in Appendix F of the S-E-A reports.

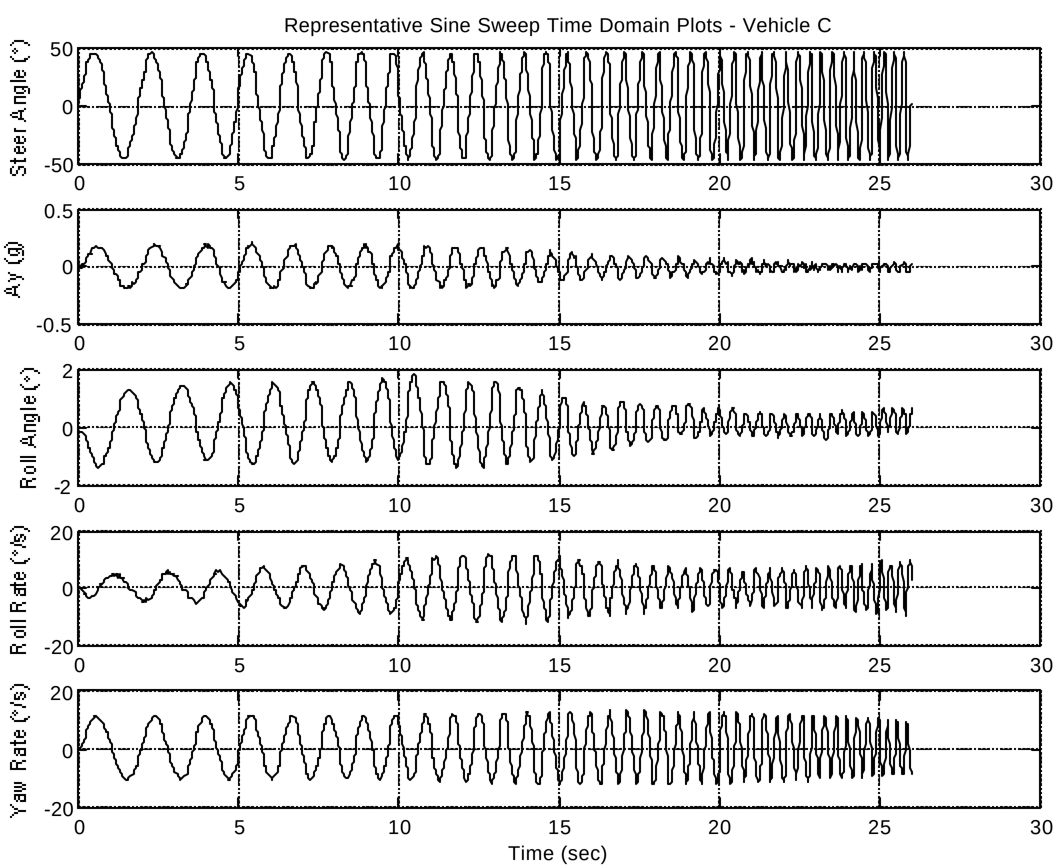

Vehicle A - 30 mph J-Turn Right
Runs: 115 and 127
Steer Angle (deg)
Time (sec)
Lateral Acceleration (g)
Speed (mph)
Dropped Throttle
Constant Throttle
Roll Angle (deg)
Yaw Rate (deg/sec)

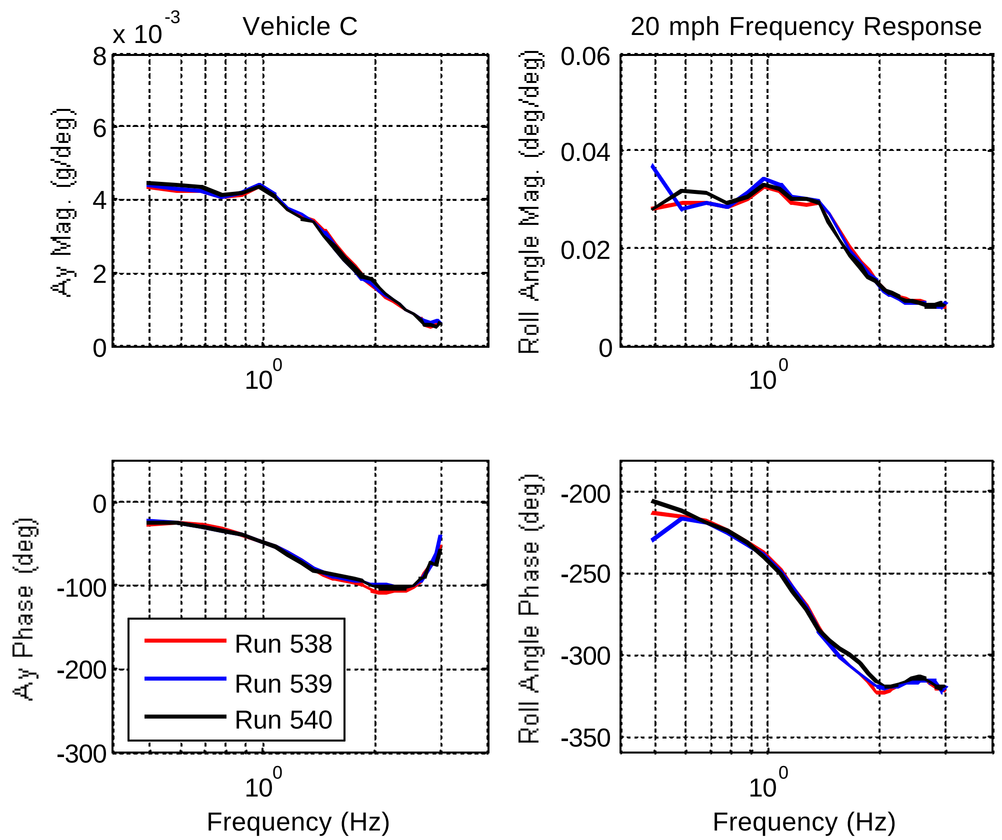
65


Vehicle A - 30 mph J-Turn Left
Runs: 117 and 131
Steer Angle (deg)
Time (sec)
Lateral Acceleration (g)
Speed (mph)
Dropped Throttle
Constant Throttle
Roll Angle (deg)
Yaw Rate (deg/sec)

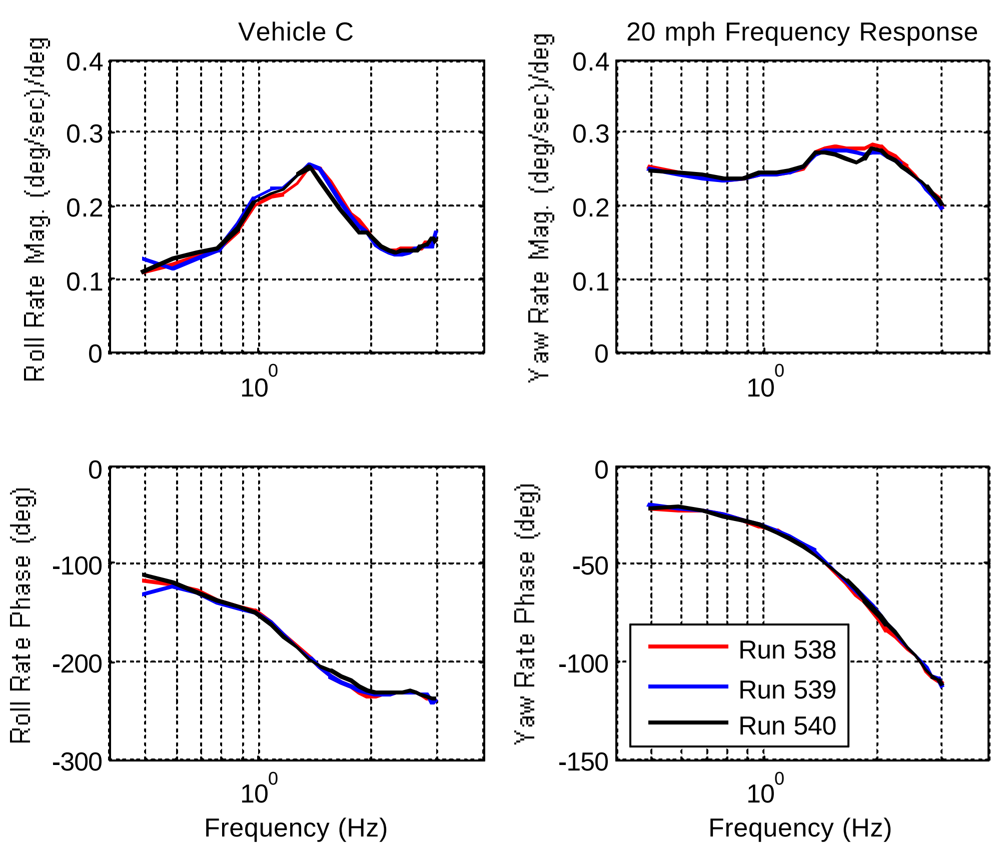
Sinusoidal Sweep Steering (Frequency Response) Tests (20 mph)

- Nominal constant speed of 20 mph
- Steering in a sinusoidal manner with steering amplitude necessary to generate nominally 0.1-0.3 g of lateral acceleration (steering amplitudes between 35º and 50º were used for these tests)
- Steering input frequencies swept from 0.5 to 3.5 Hz over the course of 40 cycles.
- The sinusoidal sweep steering tests were done to investigate any issues that might result from exciting a resonant frequency in the vehicles' responses.
- Detailed results from the sinusoidal sweep steering tests are contained in Appendix G of the S-E-A reports.





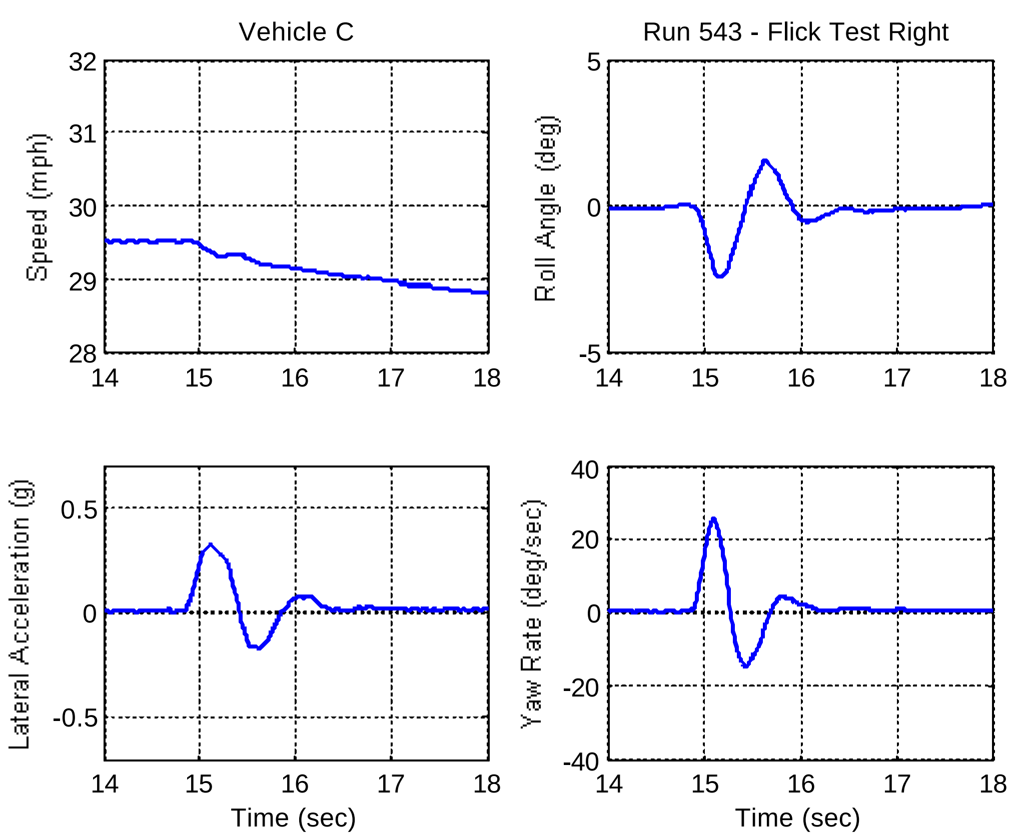
Vehicle C
20 mph Frequency Response
x 10^-3
Ay Mag. (g/deg)
Roll Angle Mag. (deg/deg)
Ay Phase (deg)
Roll Angle Phase (deg)
Run 538
Run 539
Run 540
Frequency (Hz)

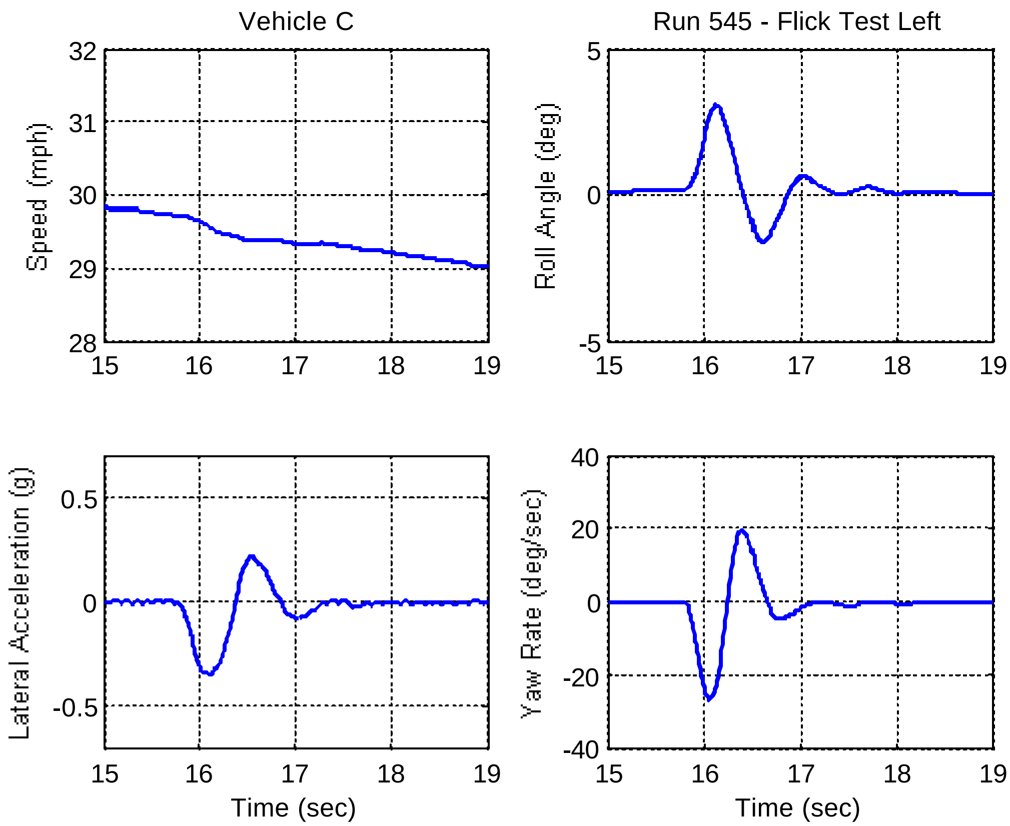


Vehicle C
20 mph Frequency Response
Roll Rate Mag. (deg/sec)/deg
Yaw Rate Mag. (deg/sec)/deg
Roll Rate Phase (deg)
Yaw Rate Phase (deg)
Run 538
Run 539
Run 540
Frequency (Hz)

Constant Speed (30 mph) Steering Flick Tests

- Nominal constant speed of 30 mph
- Steering in Right and Left Directions
- Steering flick tests involve driving the vehicles along a straight-line path and quickly 'flicking' the steering wheel to nominally 90 degrees and letting go of the steering wheel.
- The steering flick maneuvers were used to evaluate the stability of the vehicles' responses to open-loop, free control steering inputs. An unstable vehicle may respond with oscillatory or divergent behavior during a flick test.
- Also, if the vehicle responses do not return to a close-to-zero position after the steering is released, this could be an indication too little self aligning steering moment or possibly too much friction in the steering system.
- Detailed results from the steering flick tests are contained in Appendix H of the S-E-A reports.

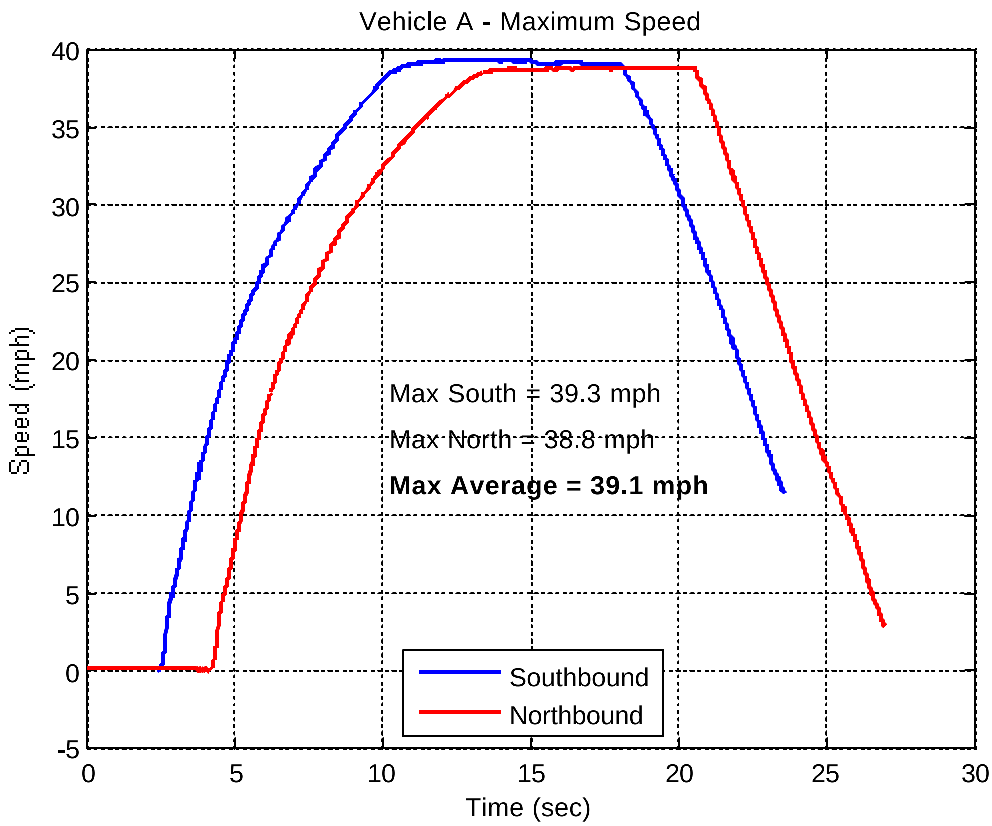




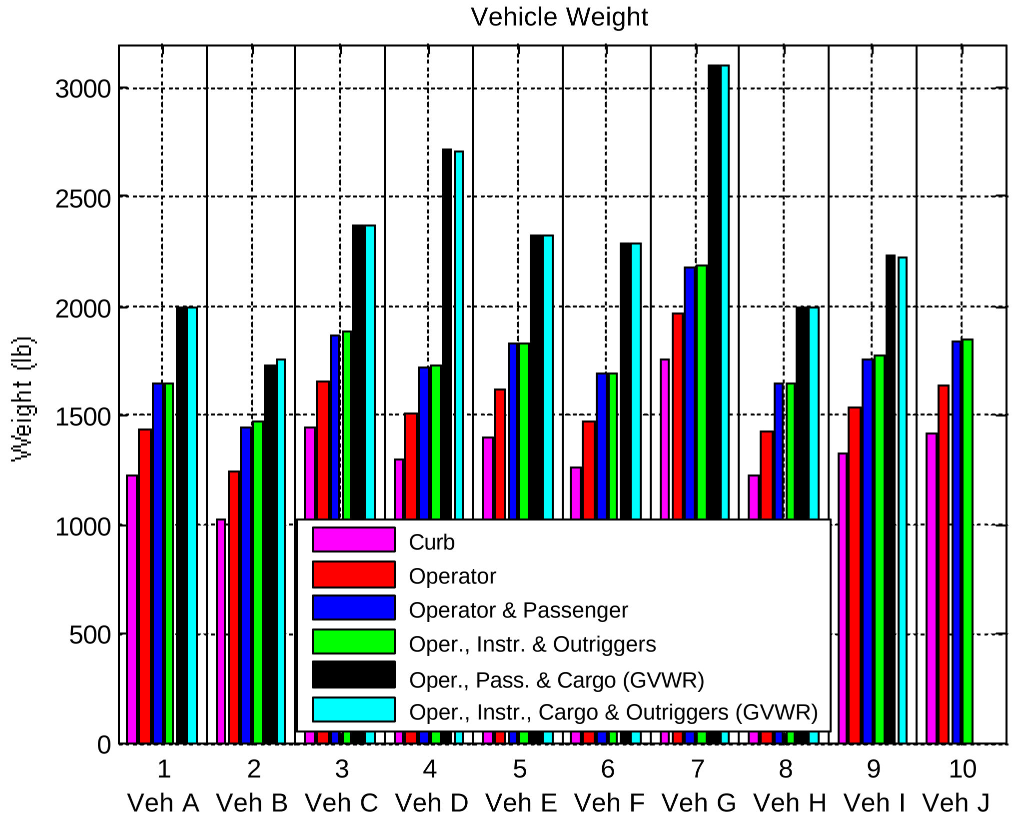
Maximum Speed Tests

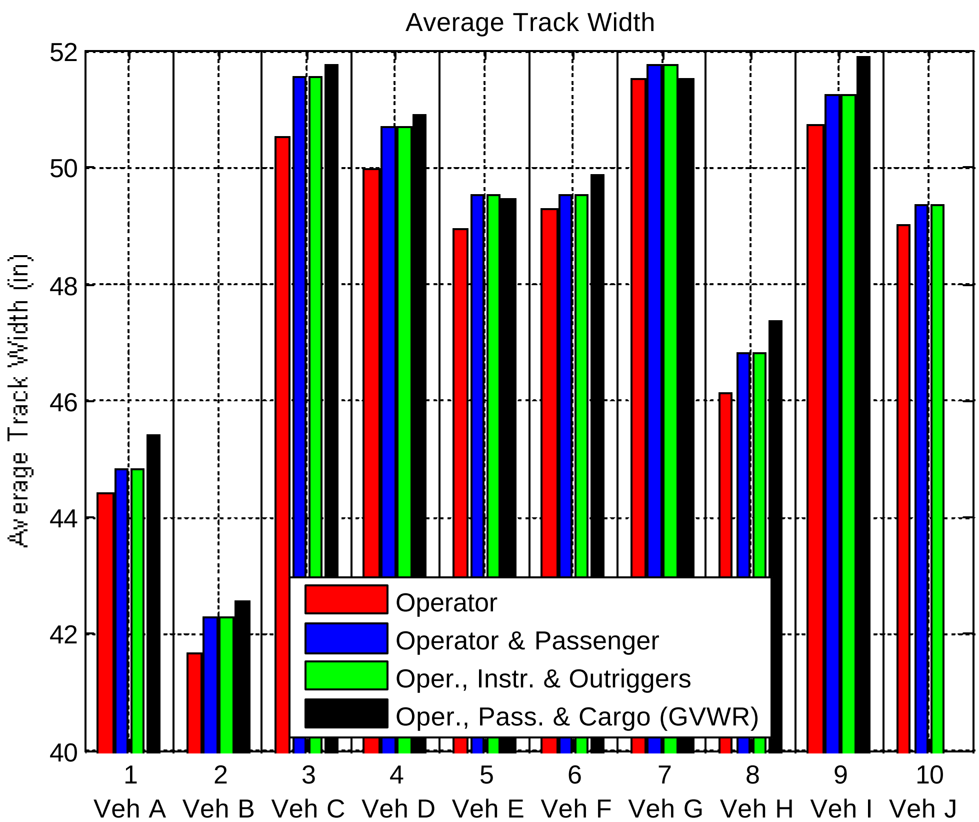
- For the maximum speed tests, the test driver drove each vehicle along a straight-line path at maximum throttle until maximum speed was reached. Tests were run in two opposite directions, along the direction up the TRC VDA one percent grade (roughly northward) and along the direction down the TRC VDA one percent grade (roughly southward).

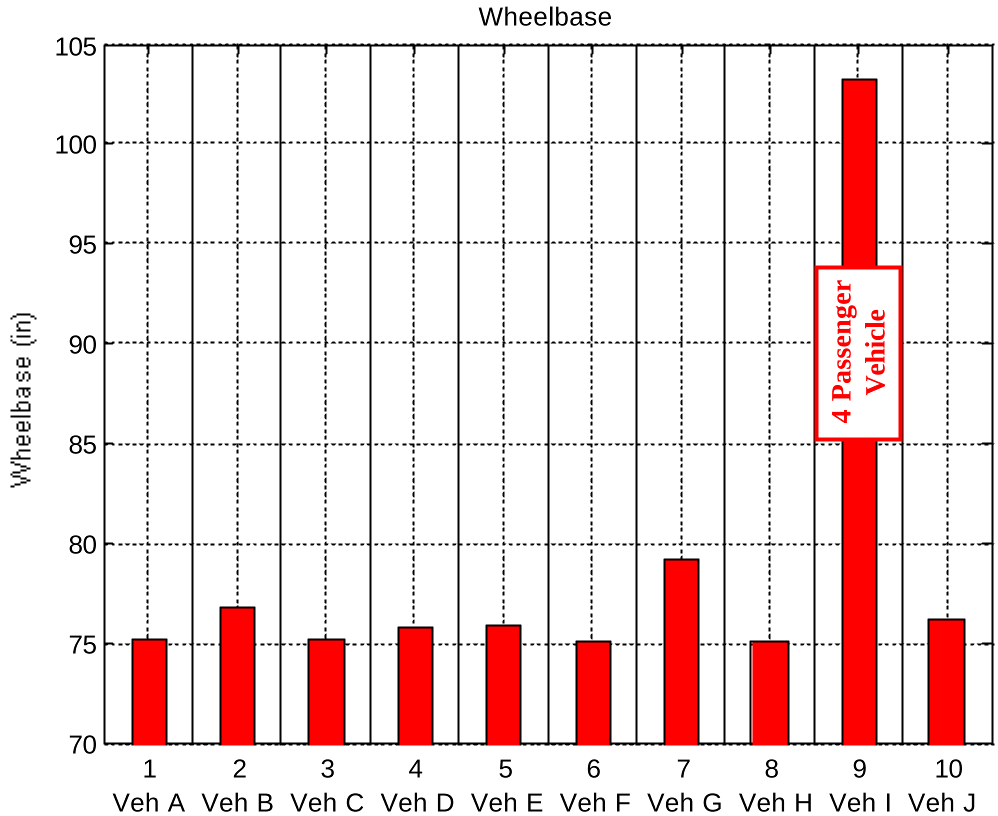
- Detailed results from the maximum speed tests are contained in Appendix I for all vehicles in both loading conditions.

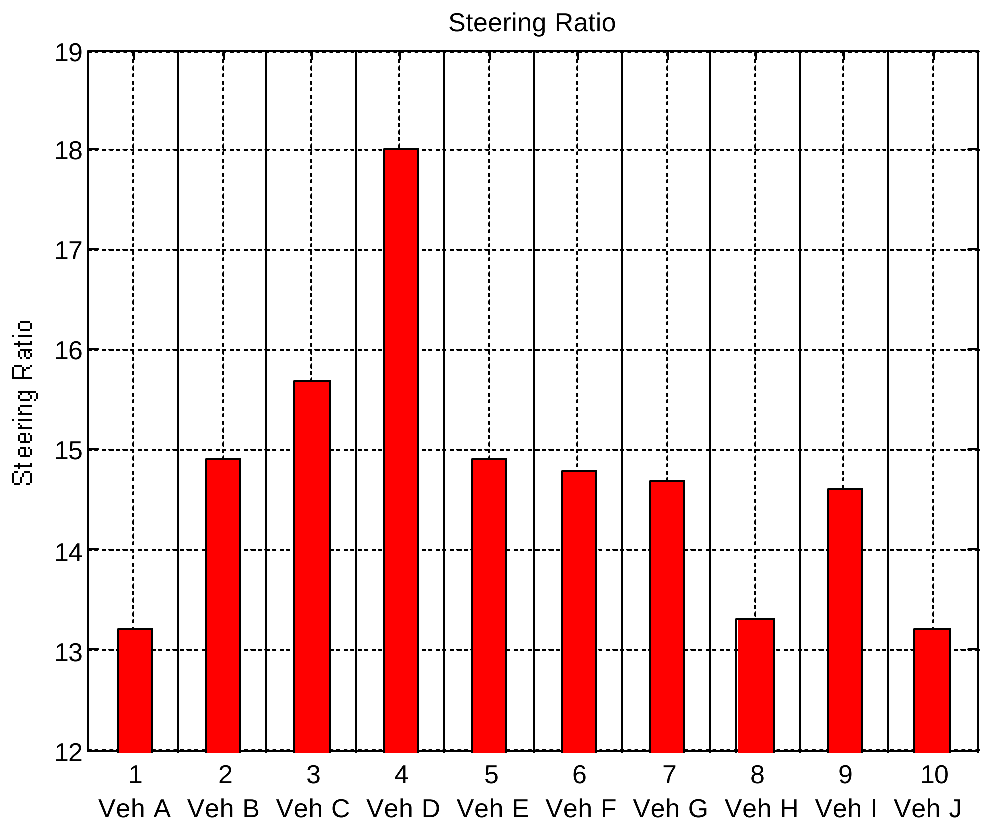


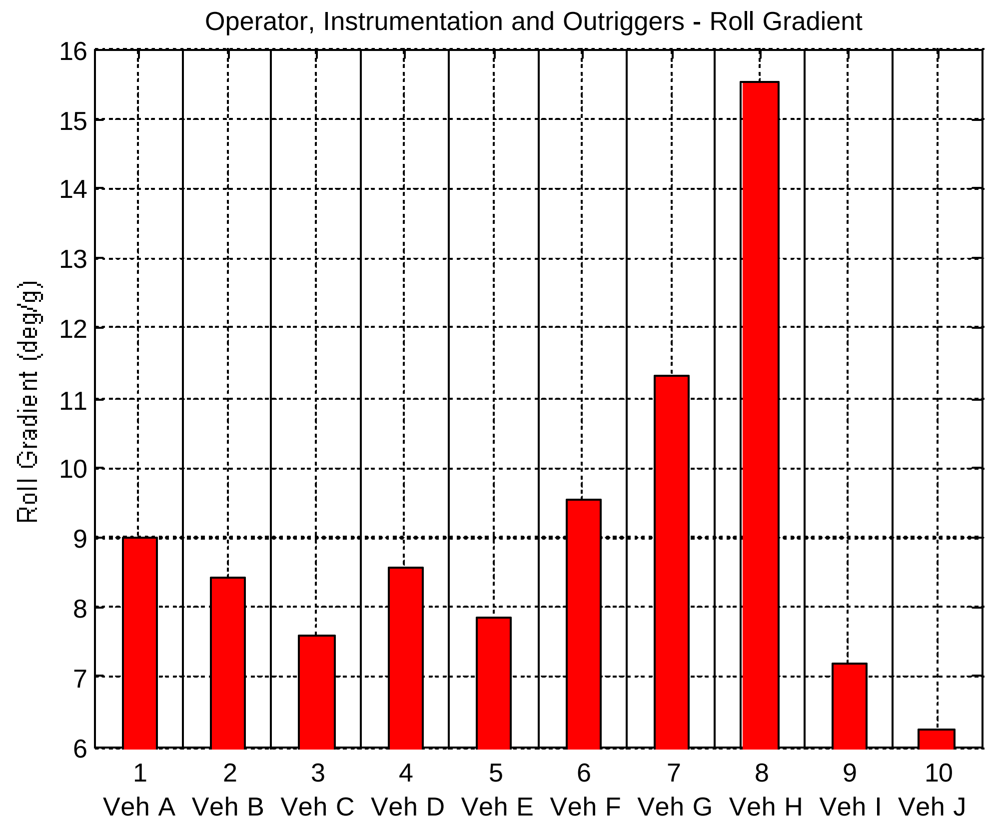
Selection of Summary Results
From Appendix B of S-E-A Reports


Vehicle Weight
Weight (lb)
0
500
1000
1500
2000
2500
3000
1 Veh A
2 Veh B
3 Veh C
4 Veh D
5 Veh E
6 Veh F
7 Veh G
8 Veh H
9 Veh I
10 Veh J
Curb
Operator
Operator & Passenger
Oper., Instr. & Outriggers
Oper., Pass. & Cargo (GVWR)
Oper., Instr., Cargo & Outriggers (GVWR)


Average Track Width
Average Track Width (in)
40
42
44
46
48
50
52
1 Veh A
2 Veh B
3 Veh C
4 Veh D
5 Veh E
6 Veh F
7 Veh G
8 Veh H
9 Veh I
10 Veh J
Operator
Operator & Passenger
Oper., Instr. & Outriggers
Oper., Pass. & Cargo (GVWR)

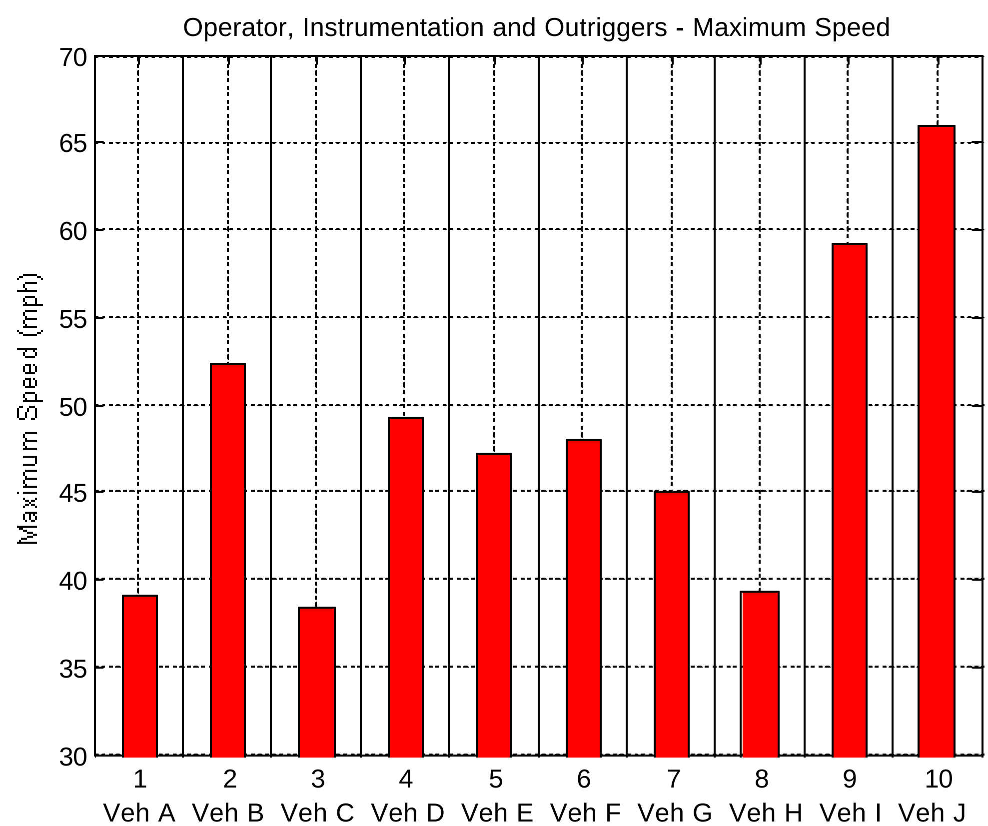

Wheelbase
Wheelbase (in)
105
100
95
90
85
80
75
70
4 Passenger Vehicle
1 2 3 4 5 6 7 8 9 10
Veh A Veh B Veh C Veh D Veh E Veh F Veh G Veh H Veh I Veh J


Steering Ratio
Steering Ratio
19
18
17
16
15
14
13
12
1 2 3 4 5 6 7 8 9 10
Veh A Veh B Veh C Veh D Veh E Veh F Veh G Veh H Veh I Veh J



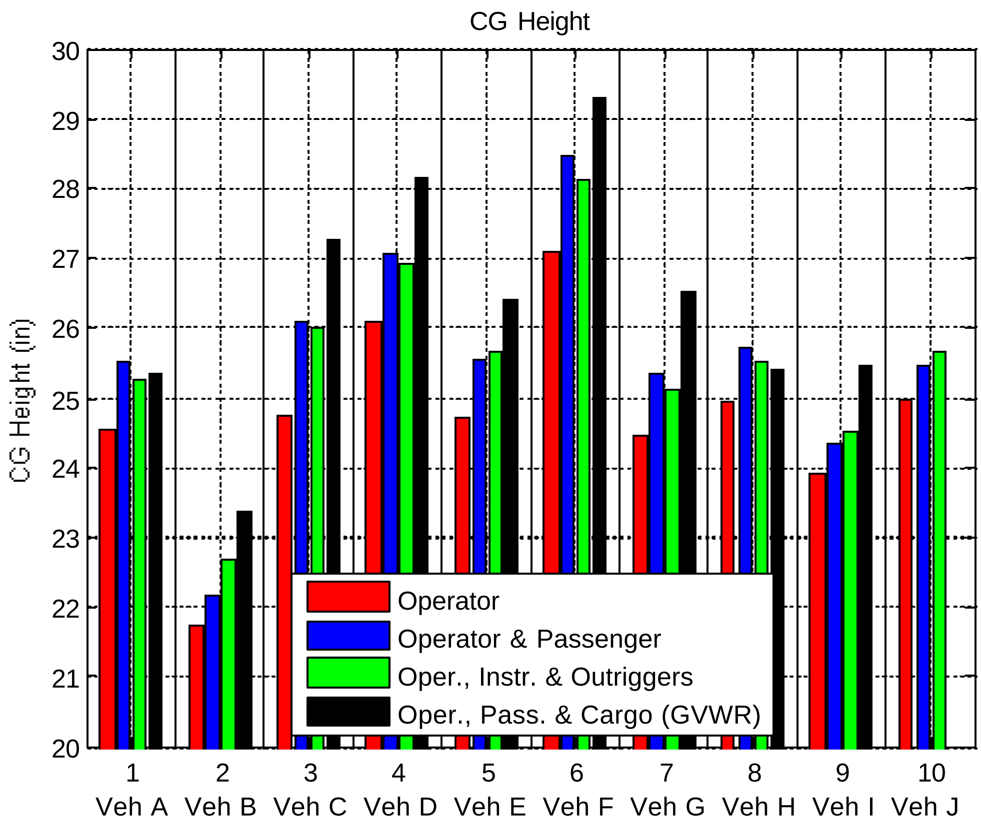
Operator, Instrumentation and Outriggers - Roll Gradient
Roll Gradient (deg/g)
16
15
14
13
12
11
10
9
8
7
6
1 2 3 4 5 6 7 8 9 10
Veh A Veh B Veh C Veh D Veh E Veh F Veh G Veh H Veh I Veh J

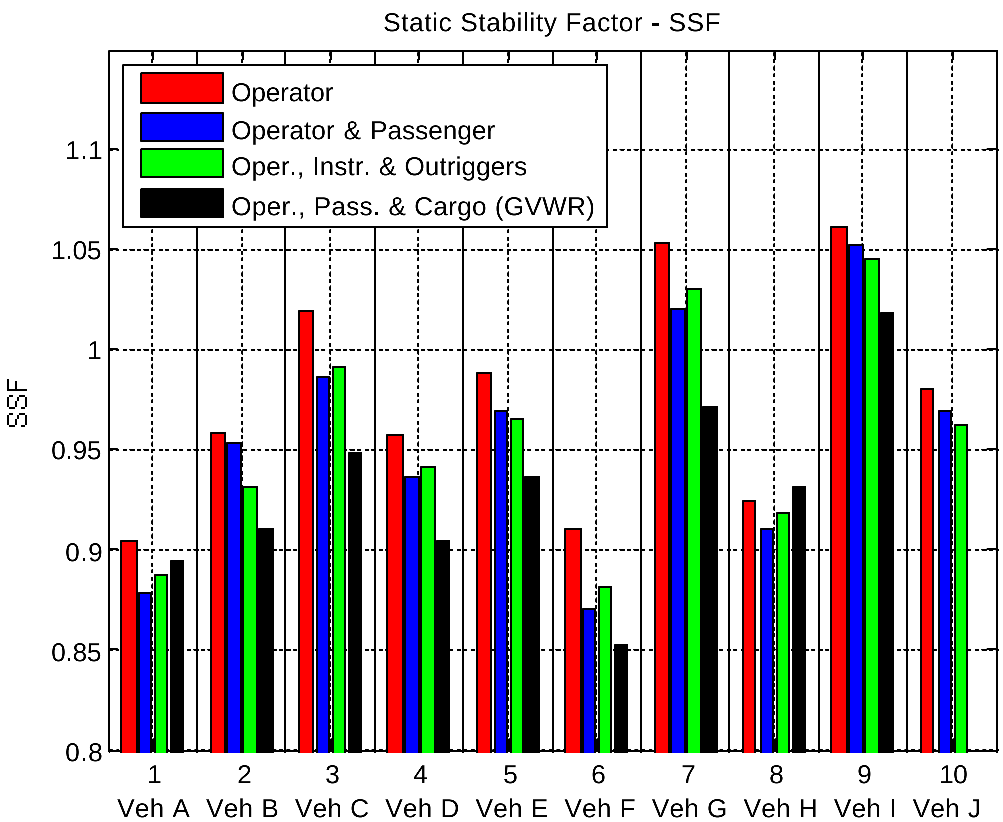
81

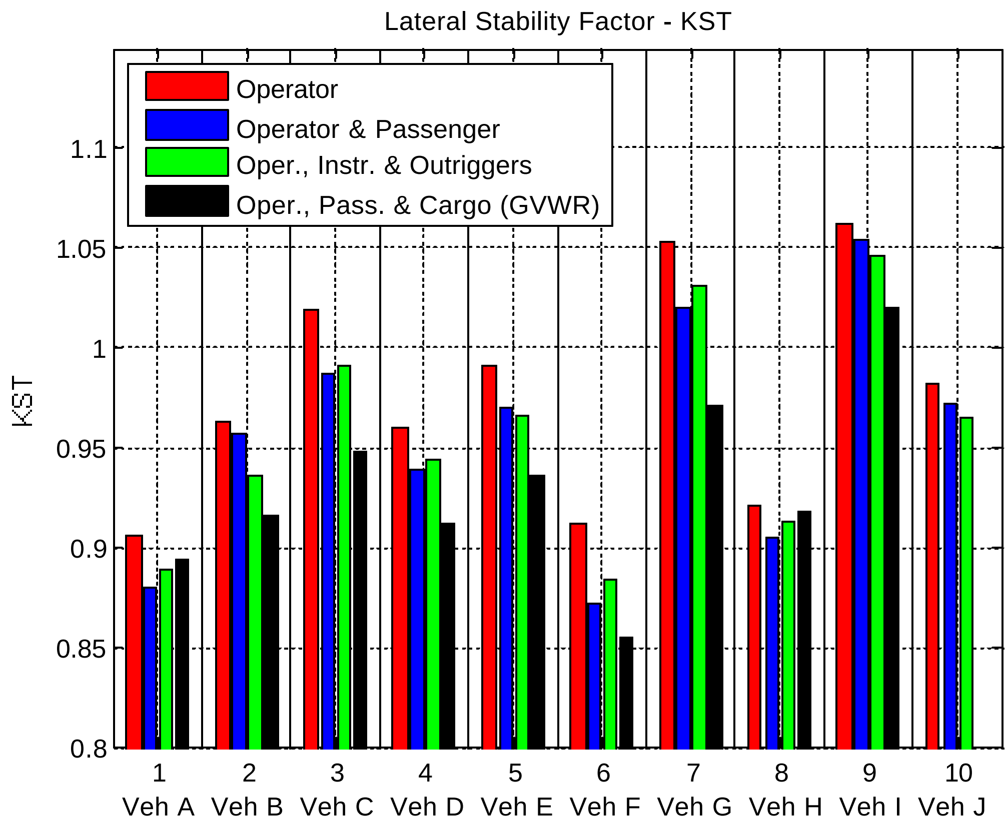


Operator, Instrumentation and Outriggers - Maximum Speed
Maximum Speed (mph)
70
65
60
55
50
45
40
35
30
1 2 3 4 5 6 7 8 9 10
Veh A Veh B Veh C Veh D Veh E Veh F Veh G Veh H Veh I Veh J

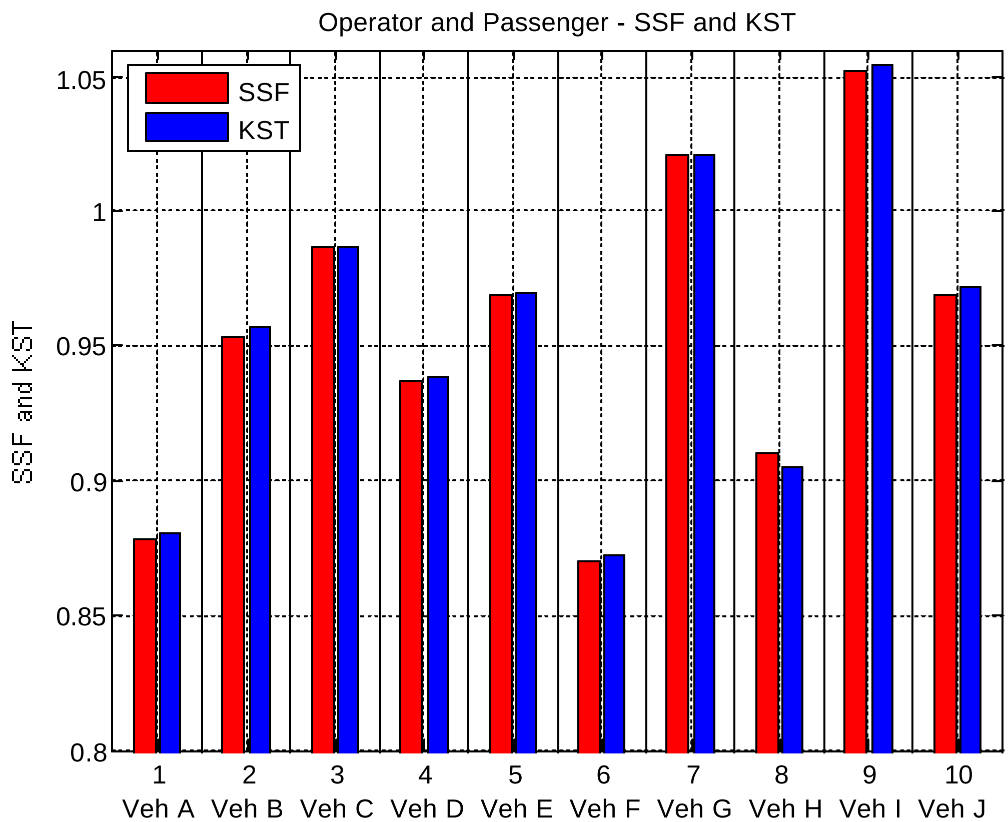
82


CG Height
CG Height (in)
30
29
28
27
26
25
24
23
22
21
20
Operator
Operator & Passenger
Oper., Instr. & Outriggers
Oper., Pass. & Cargo (GVWR)
1 2 3 4 5 6 7 8 9 10
Veh A Veh B Veh C Veh D Veh E Veh F Veh G Veh H Veh I Veh J

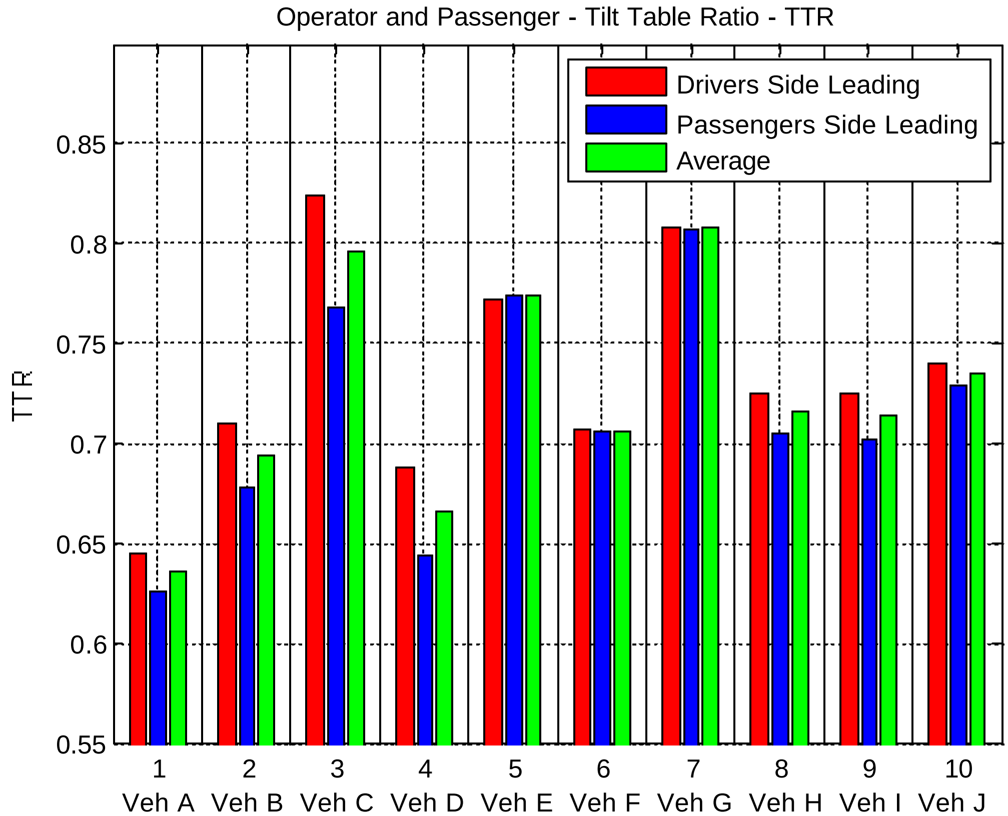

Static Stability Factor - SSF
SSF
1.1
1.05
1
0.95
0.9
0.85
0.8
Operator
Operator & Passenger
Oper., Instr. & Outriggers
Oper., Pass. & Cargo (GVWR)
1 2 3 4 5 6 7 8 9 10
Veh A Veh B Veh C Veh D Veh E Veh F Veh G Veh H Veh I Veh J


Lateral Stability Factor - KST
Operator
Operator & Passenger
Oper., Instr. & Outriggers
Oper., Pass. & Cargo (GVWR)
KST
1.1
1.05
1
0.95
0.9
0.85
0.8
1 2 3 4 5 6 7 8 9 10
Veh A Veh B Veh C Veh D Veh E Veh F Veh G Veh H Veh I Veh J

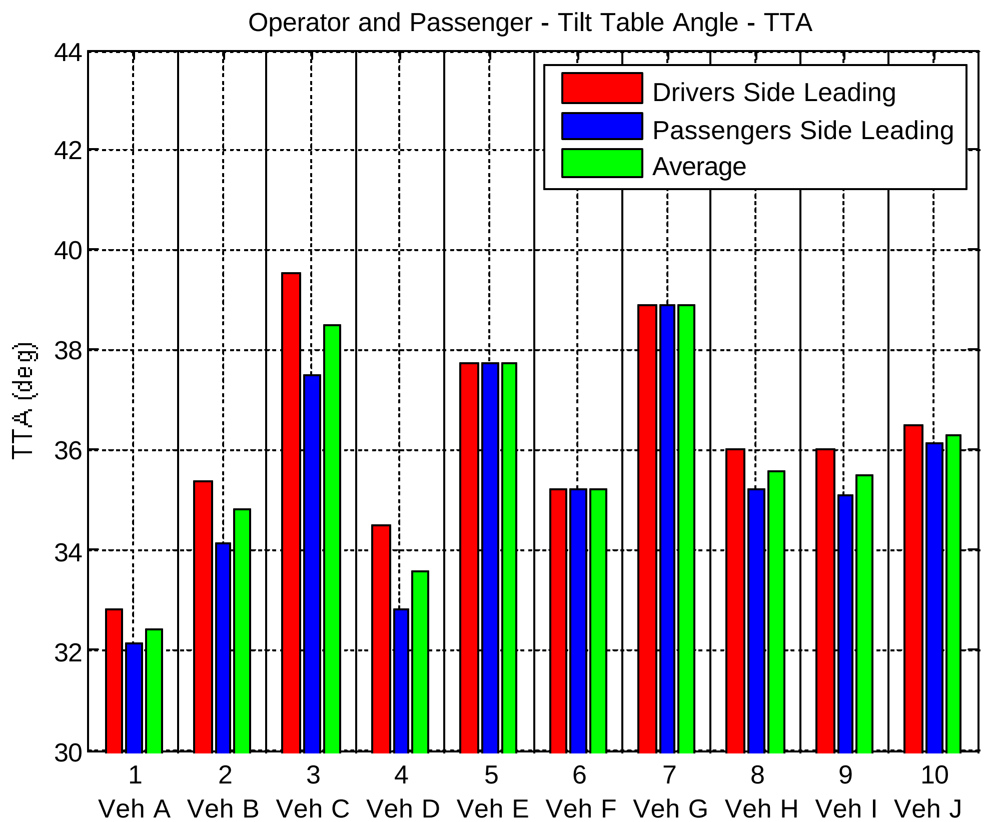
85


Operator and Passenger - SSF and KST
SSF
KST
SSF and KST
1.05
1
0.95
0.9
0.85
0.8
1 2 3 4 5 6 7 8 9 10
Veh A Veh B Veh C Veh D Veh E Veh F Veh G Veh H Veh I Veh J

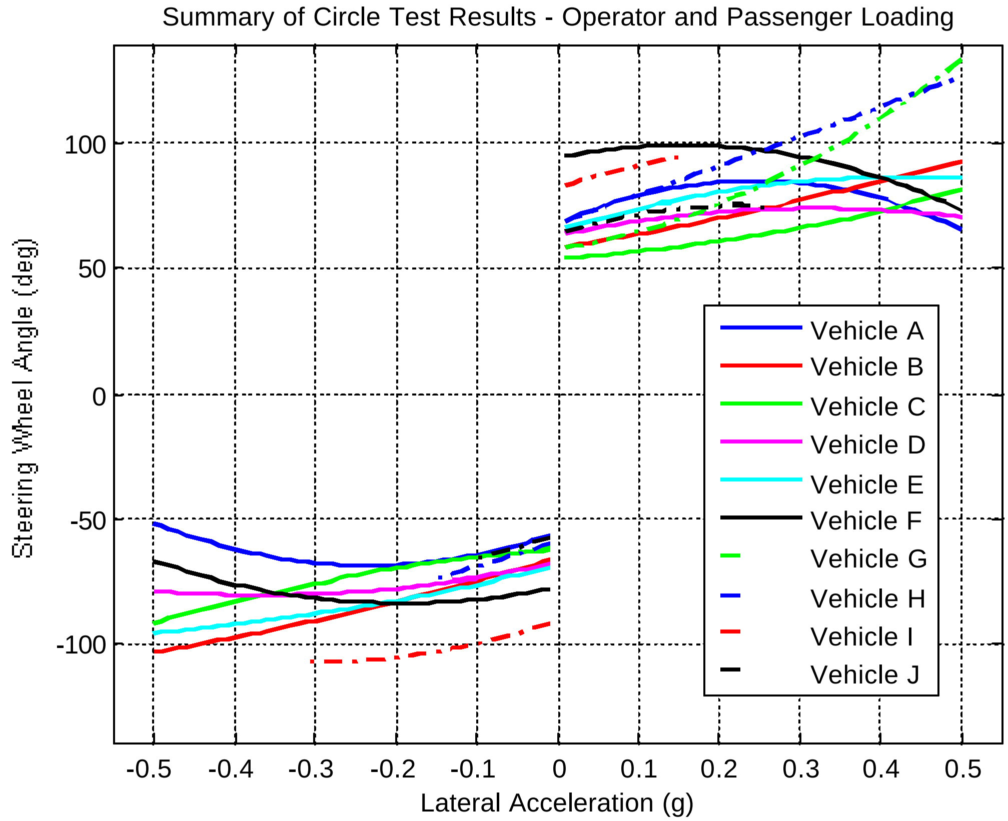
86

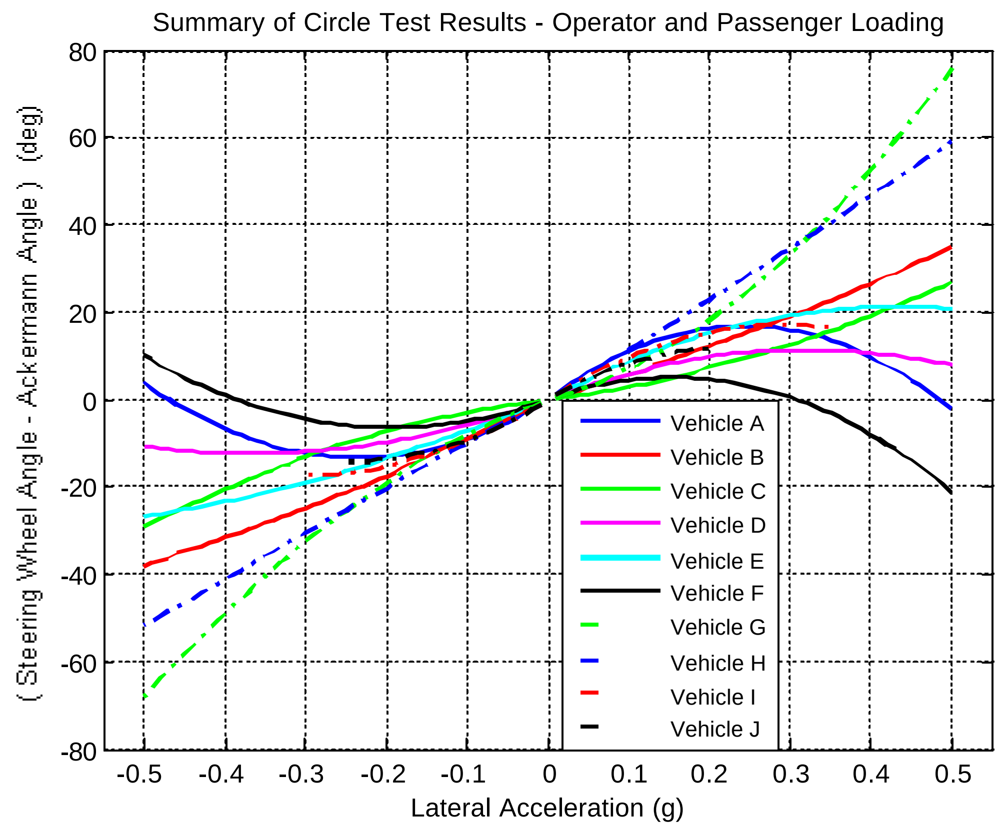

Operator and Passenger - Tilt Table Ratio - TTR
Drivers Side Leading
Passengers Side Leading
Average
TTR
0.55
0.6
0.65
0.7
0.75
0.8
0.85
1 Veh A
2 Veh B
3 Veh C
4 Veh D
5 Veh E
6 Veh F
7 Veh G
8 Veh H
9 Veh I
10 Veh J

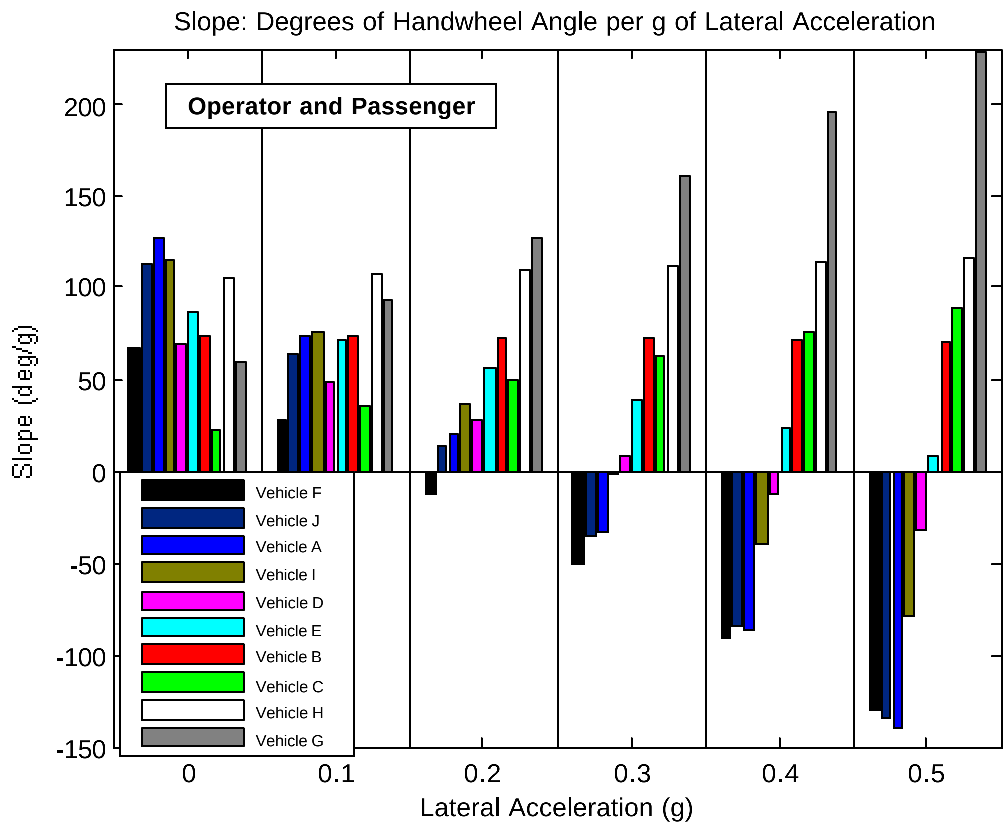
87


Operator and Passenger - Tilt Table Angle - TTA
Drivers Side Leading
Passengers Side Leading
Average
TTA (deg)
30
32
34
36
38
40
42
44
1 Veh A
2 Veh B
3 Veh C
4 Veh D
5 Veh E
6 Veh F
7 Veh G
8 Veh H
9 Veh I
10 Veh J

88


Summary of Circle Test Results - Operator and Passenger Loading
Steering Wheel Angle (deg)
Lateral Acceleration (g)
100
50
0
-50
-100
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Vehicle A
Vehicle B
Vehicle C
Vehicle D
Vehicle E
Vehicle F
Vehicle G
Vehicle H
Vehicle I
Vehicle J


Summary of Circle Test Results - Operator and Passenger Loading
(Steering Wheel Angle - Ackermann Angle) (deg)
Lateral Acceleration (g)
80
60
40
20
0
-20
-40
-60
-80
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Vehicle A
Vehicle B
Vehicle C
Vehicle D
Vehicle E
Vehicle F
Vehicle G
Vehicle H
Vehicle I
Vehicle J



Constant Radius (100 ft) Circle Tests

Lateral Acceleration Level at Point of Transition from Understeer to Oversteer (Operator and Passenger Loading)

	Clockwise (g)	Counterclockwise (g)	Average (g)	
Vehicle A	**0.24**	**0.23**	**0.24**	**OS**
Vehicle B	**NA**	**NA**	**NA**	
Vehicle C	**NA**	**NA**	**NA**	
Vehicle D	**0.32**	**0.37**	**0.35**	**OS**
Vehicle E	**0.44**	**NA**	**NA**	
Vehicle F	**0.15**	**0.19**	**0.17**	**OS**
Vehicle G	**NA**	**NA**	**NA**	
Vehicle H	**NA**	**NA**	**NA**	
Vehicle I	**0.29**	**0.30**	**0.30**	**OS**
Vehicle J	**0.22**	**0.24**	**0.23**	**OS**

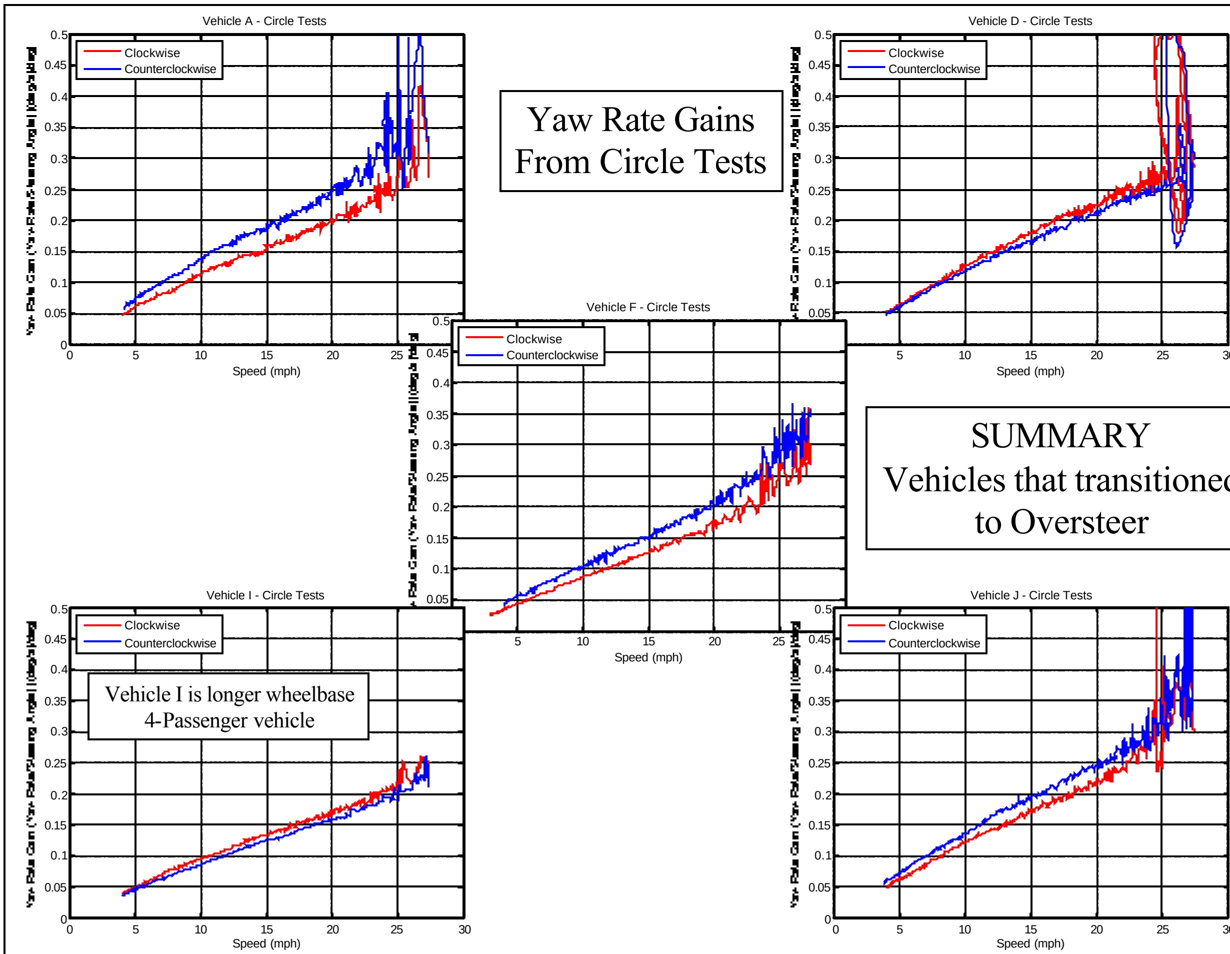
Constant Speed (30 mph) Slowly Increasing Steer Tests

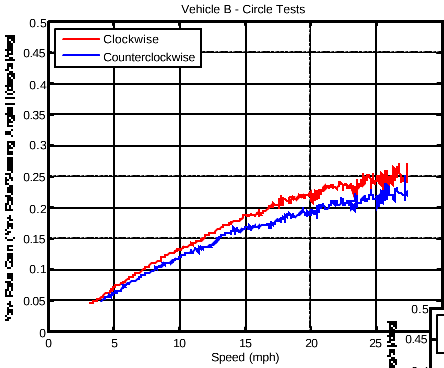
Lateral Acceleration Level at Point of Transition from Understeer to Oversteer (Operator and Passenger Loading)

	Right Turn (g)	Left Turn (g)	Average (g)	
Vehicle A	0.40	0.33	0.37	OS
Vehicle B	NA	NA	NA	
Vehicle C	NA	NA	NA	
Vehicle D	0.35	0.44	0.40	OS
Vehicle E	NA	NA	NA	
Vehicle F	0.39	0.42	0.41	OS
Vehicle G	NA	NA	NA	
Vehicle H	NA	NA	NA	
Vehicle I	0.43	0.46	0.45	OS
Vehicle J	0.34	0.40	0.36	OS

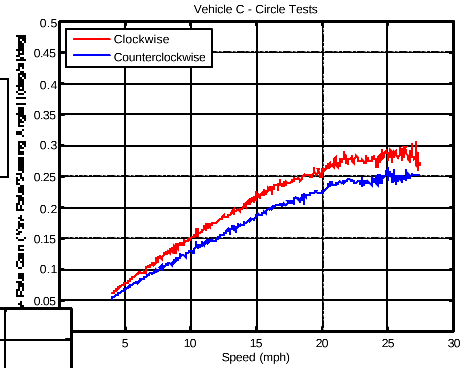
Yaw Rate Gains From Circle Tests

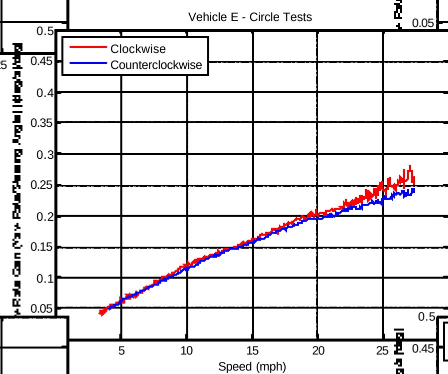
SUMMARY
Vehicles that transitioned to Oversteer



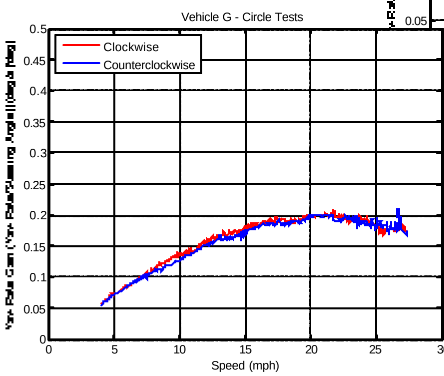


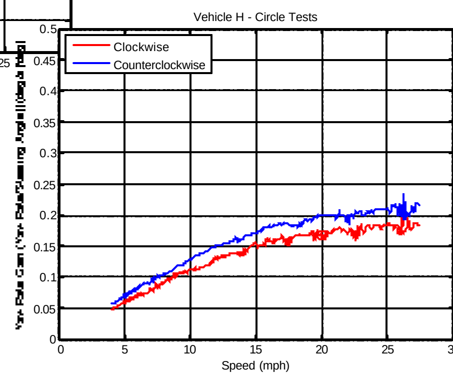
Yaw Rate Gains From Circle Tests

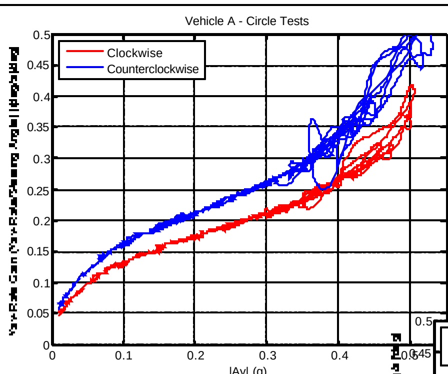




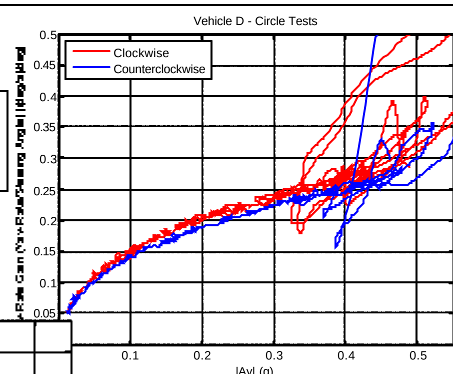
SUMMARY
Vehicles that did not transition to Oversteer

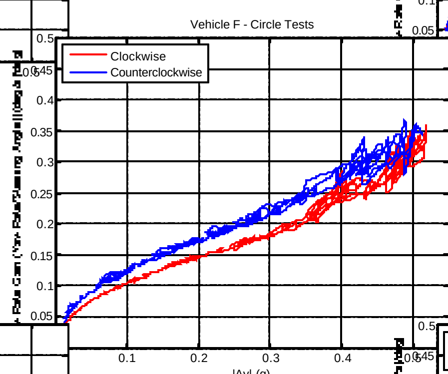




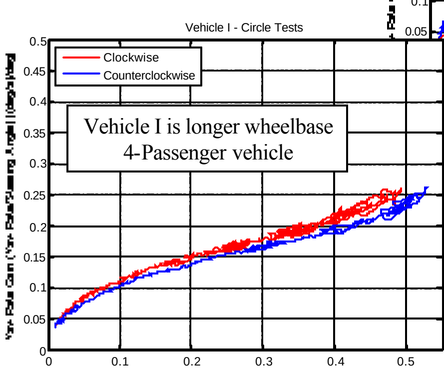


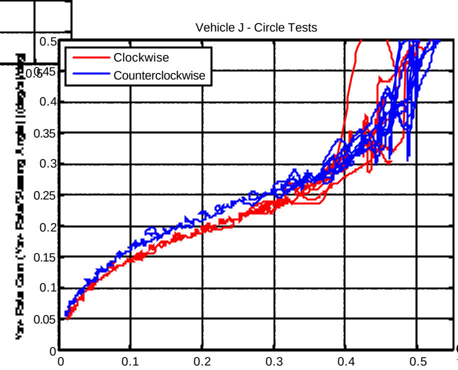
Yaw Rate Gains From Circle Tests



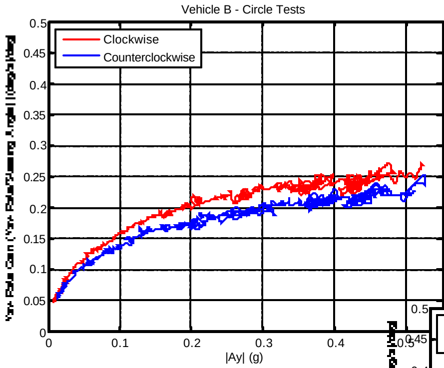


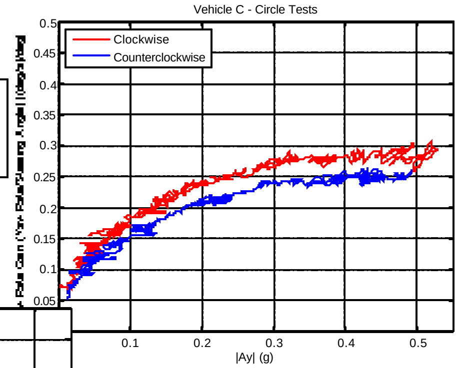
SUMMARY
Vehicles that transitioned to Oversteer

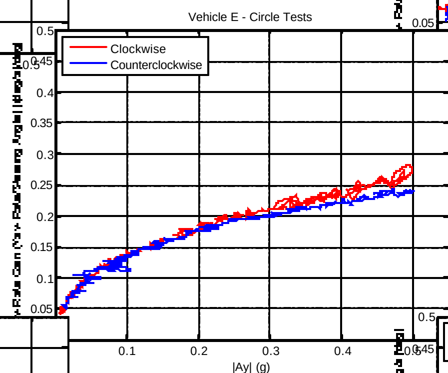




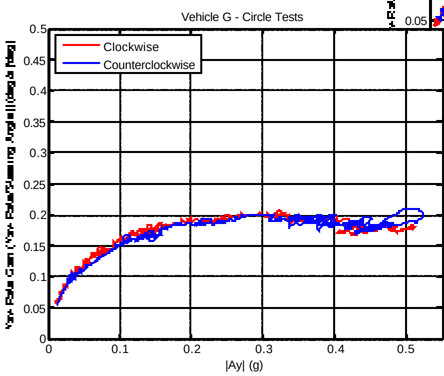
Yaw Rate Gains From Circle Tests

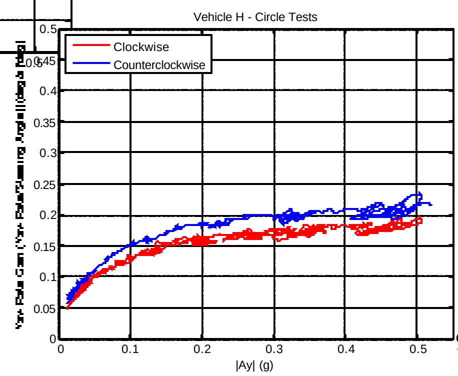


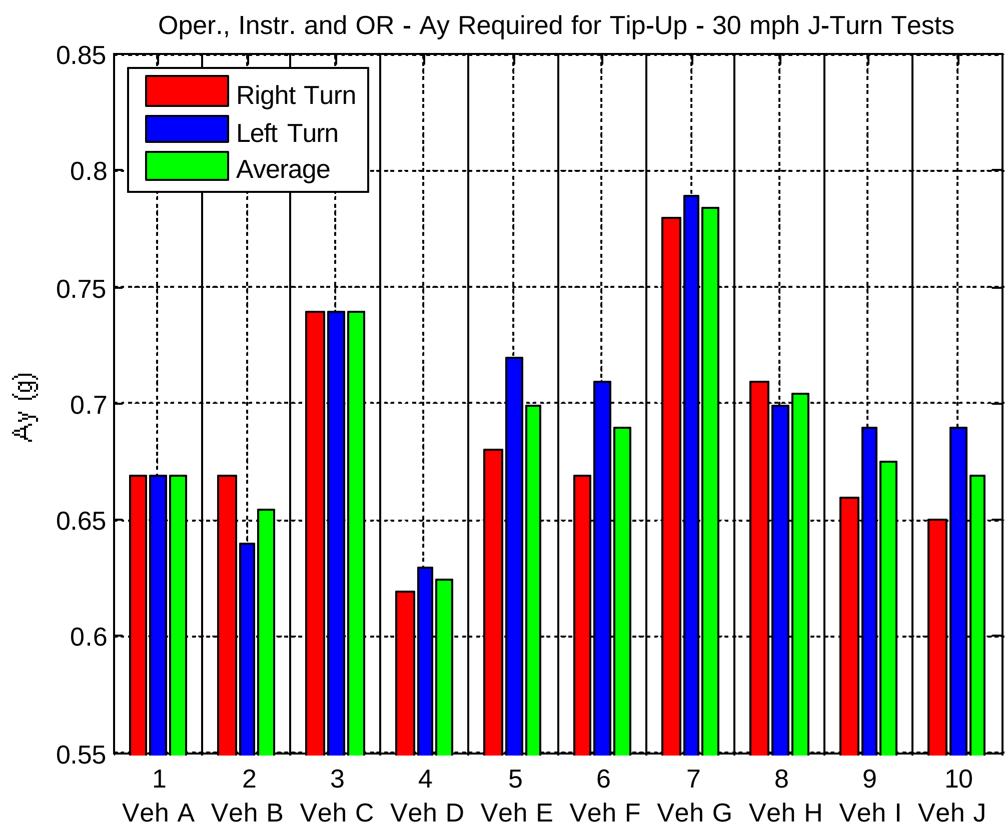


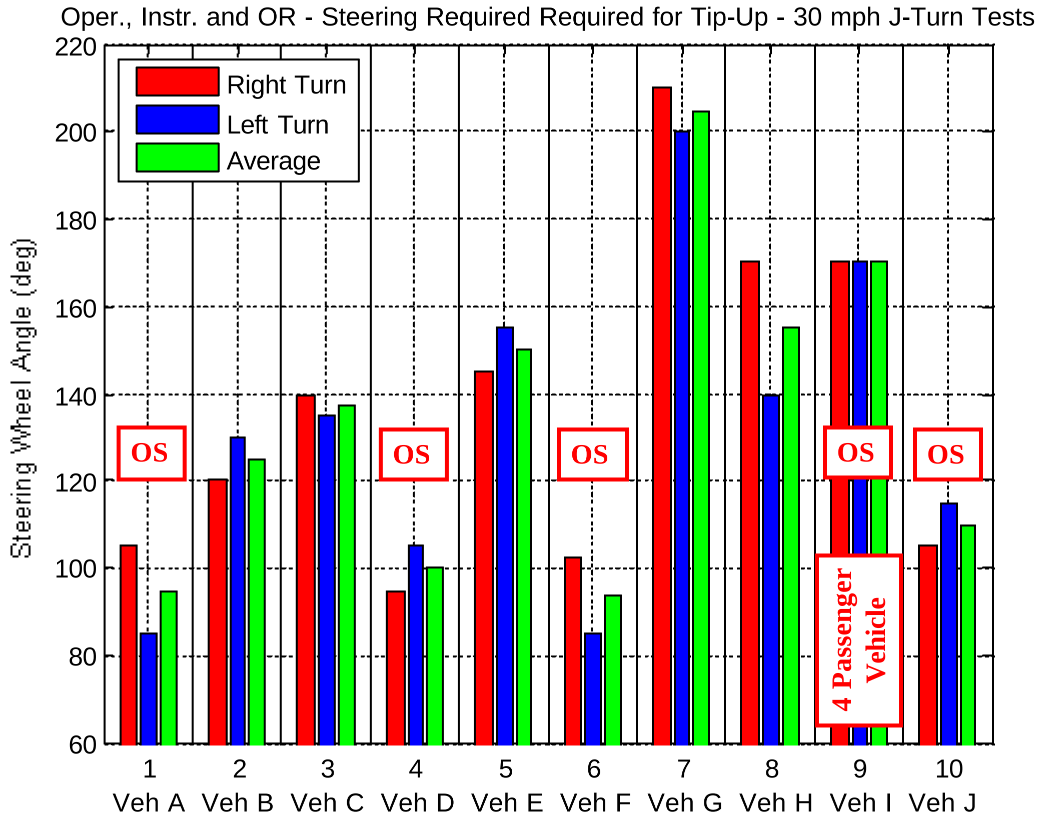


SUMMARY
Vehicles that did not transition to Oversteer





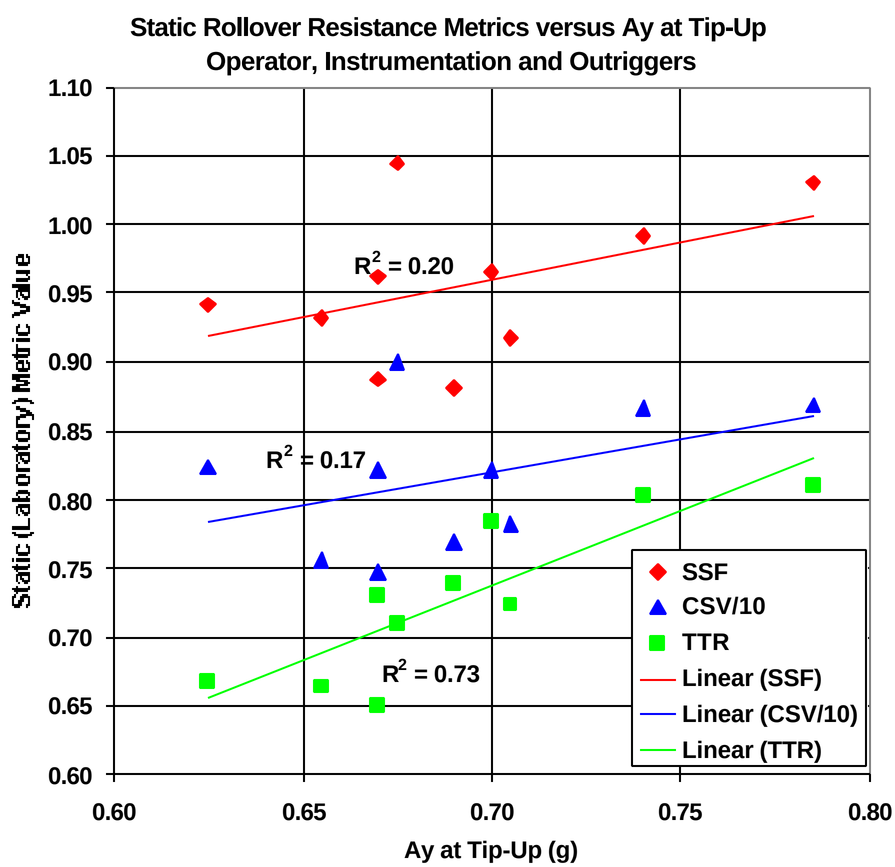


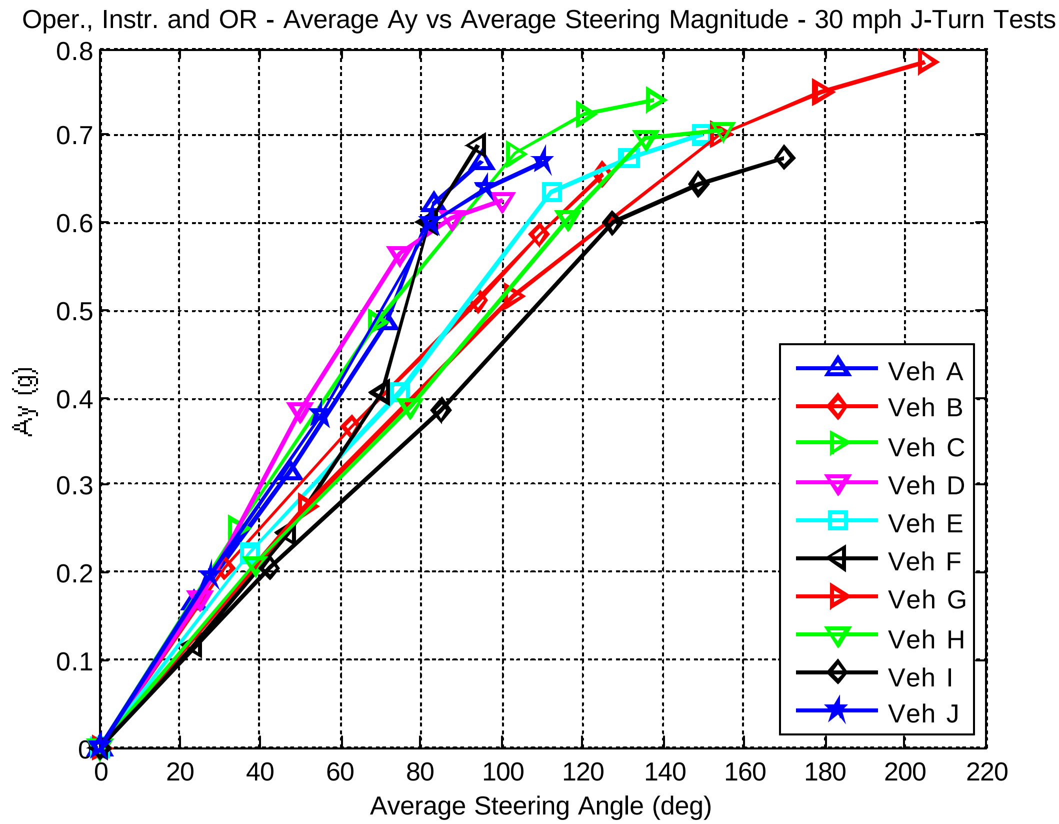


Summary of Ay and Steering Required for Tip-Up in 30 mph J-Turns and Static Rollover Resistance Metrics (Operator, Instrumentation and Outriggers)					
Vehicle	Ay at Tip-Up (g)	Steering at Tip-Up (deg)	SSF (--)	CSV/10 (mph/10)	TTR (--)
A	0.670	95.0	0.887	0.747	0.650
B	0.655	125.0	0.932	0.756	0.664
C	0.740	137.5	0.991	0.867	0.803
D	0.625	100.0	0.942	0.823	0.667
E	0.700	150.0	0.965	0.821	0.784
F	0.690	93.8	0.881	0.769	0.739
G	0.785	205.0	1.031	0.869	0.810
H	0.705	155.0	0.918	0.782	0.724
I	0.675	170.0	1.045	0.900	0.712
J	0.670	110.0	0.962	0.821	0.730

Vehicle Ascending Rank Order of Ay and Steering Required for Tip-Up in J-Turns and Static Rollover Resistance Metrics (Operator, Instrumentation and Outriggers)				
Ay at Tip-Up (g)	Steering at Tip-Up (deg)	SSF (--)	CSV/10 (mph/10)	TTR (--)
D	F	F	A	A
B	A	A	B	B
A	D	H	F	D
J	J	B	H	I
I	B	D	E	H
F	C	J	J	J
E	E	E	D	F
H	H	C	C	E
C	I	G	G	C
G	G	I	I	G

Vehicles A, D, F, I and J exhibited transient from Understeer to Oversteer in Circle and SIS Tests
Vehicle I is the 4-Passenger Vehicle




Oper., Instr. and OR - Average Ay vs Average Steering Magnitude - 30 mph J-Turn Tests
Ay (g)
Average Steering Angle (deg)
Veh A
Veh B
Veh C
Veh D
Veh E
Veh F
Veh G
Veh H
Veh I
Veh J

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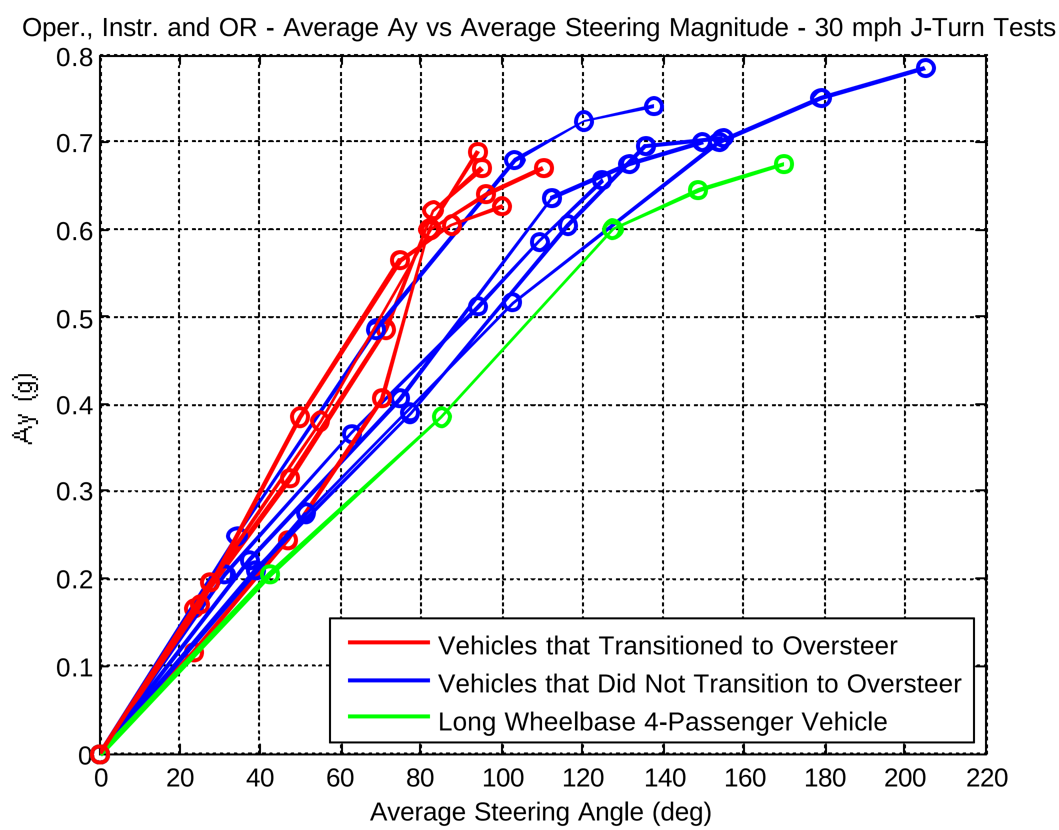
Oper., Instr. and OR - Average Ay vs Average Steering Magnitude - 30 mph J-Turn Tests
Ay (g)
Average Steering Angle (deg)
Vehicles that Transitioned to Oversteer
Vehicles that Did Not Transition to Oversteer
Long Wheelbase 4-Passenger Vehicle

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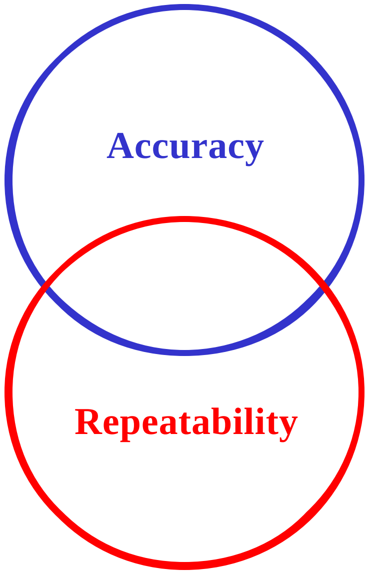
Comments Regarding Accuracy and Repeatability In Laboratory and Dynamic Tests



- A measurement can be very repeatable and not accurate
- Adherence to exacting test methodologies is needed to have accurate tests
- Adherence to exacting test methodologies is needed to have repeatable tests
- Test-to-test and lab-to-lab variability can have an influence on perceived accuracy and repeatability

Comments Regarding Accuracy and Repeatability In Dynamic Tests

- Adherence to exacting test methodologies is needed to have accurate tests
  - Properly calibrated transducers (sensors)
  - Properly mounted transducers (e.g. making measurements at the vehicles' CG locations)
  - Proper data collection and post-processing
  - Data quality checks of sensor data
- Adherence to exacting test methodologies is needed to have repeatable tests
  - Efforts to minimize test-to-test variation
    - Control over test inputs (e.g. steering robot, speed control, etc.)
    - Control over test condition (e.g. surface conditions, wind, etc.)
    - Control of vehicle conditions (e.g. secure loading, tires, fuel, etc.)

Comments Regarding S-E-A's Lateral Acceleration Measurements:

- S-E-A's sensor measurements of ground plane lateral acceleration are accurate to ± 0.001 g. S-E-A's data indicates that the overall accuracy of selecting a peak Ay value for any given run is ± 0.01 g.

- S-E-A's data indicates that the repeatability of their measurements of ground plane lateral acceleration made during their dropped-throttle J–turn tests is ± 0.02 g.

- The differences between ground plane lateral acceleration in the tests with maximum steering that did not produce two-wheel lift and tests with minimum steering to produce two-wheel lift are generally within 0.01 to 0.03 g.

Concluding Comments Regarding Accuracy and Repeatability of S-E-A's Data

S-E-A's laboratory and dynamic test results are both very **accurate** and very **repeatable** – representing the state-of-the-art regarding the measurements made.

S-E-A, Ltd. Review of ROHVA Materials Related to Dropped Throttle J-Turn Tests Presented to CPSC Technical Staff on November 10, 2011 and ROHVA's May 1, 2012 Responses to CPSC Staff Questions dated February 15, 2012

Gary J. Heydinger, Ph.D., P.E.
Director Vehicle Dynamics Division

July 19, 2012

Scientific Expert Analysis™

The fact that Carr Engineering could not duplicate some of the testing results of S-E-A does not mean that the testing results of S-E-A are inaccurate or unrepeatable.

S-E-A Lateral Acceleration Measurements

- S-E-A used a sensor that provides for a direct measurement of ground plane lateral acceleration (sometimes referred to as Corrected Ay).
- S-E-A's sensor was also configured to provide ground plane lateral acceleration at the measured center of gravity of each vehicle.

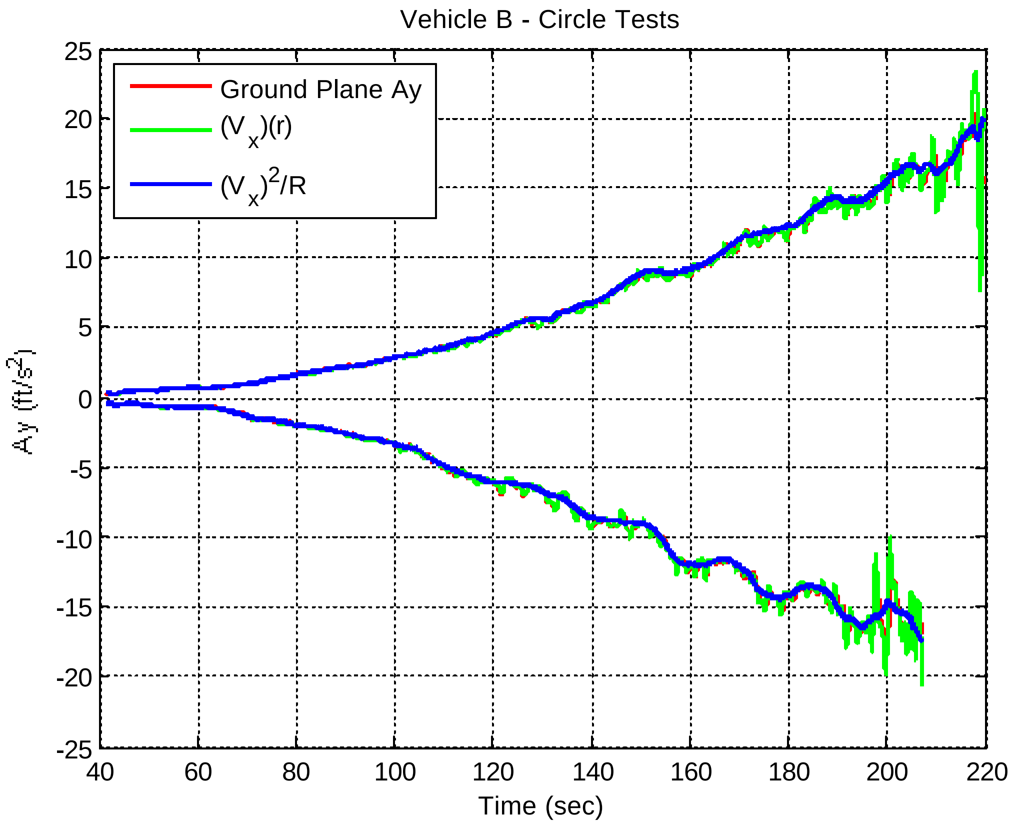
S-E-A Data Quality Checks

During SAE J266 constant radius circle tests the following fundamental relationships involving ground plane lateral acceleration (Ay), vehicle longitudinal speed (Vx), yaw rate (r), and circle radius (R) hold true:

$$Ground\ Plane\,(Corrected)\ Ay = V_x \times r = \frac{V_x^{\,2}}{R}$$

The graph on the following slide contains data measured by S-E-A during the circle tests for Vehicle B in the representative Operator plus Passenger loading condition. The plots indicate that the S-E-A data is consistent with these fundamental relationships.

S-E-A performed similar data quality checks for all vehicles tested for and reported to CPSC, and confirmed that the quality of this data for all vehicles tested was similar to that shown on the following page. The data channels used for ground plane Ay, Vx and r during these tests are the same data channels S-E-A used for all tests, including the dropped throttle J-turn tests.



Carr Engineering
Lateral Acceleration Measurements

Using a sensor like the one used by Carr Engineering, the magnitude of the measured lateral acceleration is greater than the magnitude of the ground plane lateral acceleration (Corrected Ay) during a dropped throttle J-turn maneuver.

Correct Equation for Planar Ground Plane (Corrected) Lateral Acceleration

Using a sensor like the one used by Carr Engineering, the ground plane (Corrected) lateral acceleration can be computed from the measured vehicle-body-fixed lateral acceleration and the vehicle-body-fixed vertical acceleration (both of which sense accelerations caused by the maneuver and by gravity). The ground plane (Corrected) lateral acceleration is the acceleration parallel to the road plane, and it is computed as (using SAE vehicle coordinate sign conventions):

$$Corrected\ \ Ay = Measured\ \ Ay \times cos(\phi) - Measured\ \ Az \times sin(\phi)$$

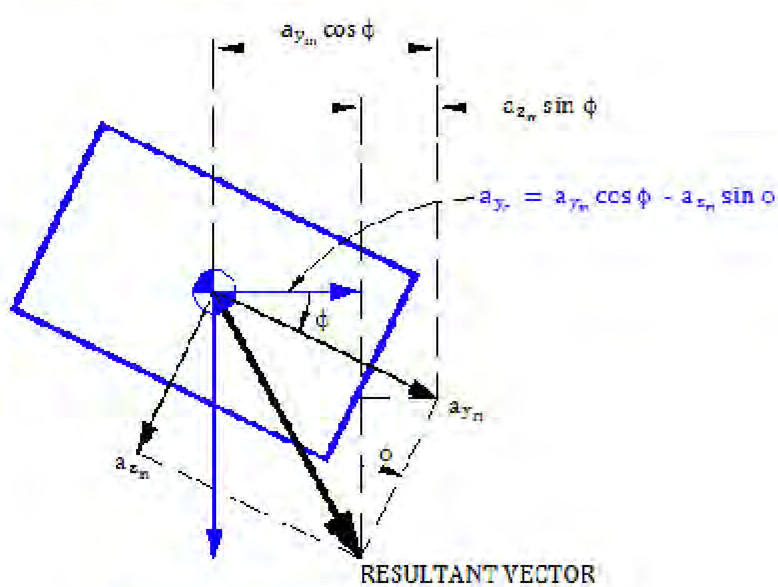
$$where\ \ \phi = body\ \ roll\ \ angle$$

See derivation on following slide and two references:

Consumer Information; New Car Assessment Program; Rollover Resistance; Final Rule, *Federal Register, Part II, Department of Transportation, NHTSA, Pg. 59274, October 14, 2003.*

American National Standard for Recreational Off-Highway Vehicles
ANSI/ROHVA 1 – 2011, 2011

a_{y_m} = Measured body - fixed lateral acceleration
a_{z_m} = Measured body - fixed vertical acceleration
a_{y_c} = Corrected (Ground Plane) lateral acceleration
ϕ = Body roll angle



$$a_{y_c} = a_{y_m} \cos\phi - a_{z_m} \sin\phi$$

Incorrect Equation used by Carr Engineering For Corrected Lateral Acceleration

$$Corrected\ \ Ay = Measured\ \ Ay - \frac{sin(body\ \ roll\ \ angle)}{cos(body\ \ roll\ \ angle)}$$

From ROHVA Responses to CPSC Staff Questions, dated February 15, 2012 – Answer to Question 19.

Using a sensor like the one used by Carr Engineering, the ground plane (Corrected) lateral acceleration can be computed from the measured vehicle-body-fixed lateral acceleration and the vehicle-body-fixed vertical acceleration. Using the equation above, Carr Engineering essentially added to the magnitude of the measured Ay, instead of subtracting from the magnitude of the measured Ay. In addition to the major sign error, the equation above also contains trigonometric errors.

S-E-A Estimation of Correctly Computed Carr Engineering Ground Plane Lateral Acceleration Given Carr Engineering Reported Data and Equation

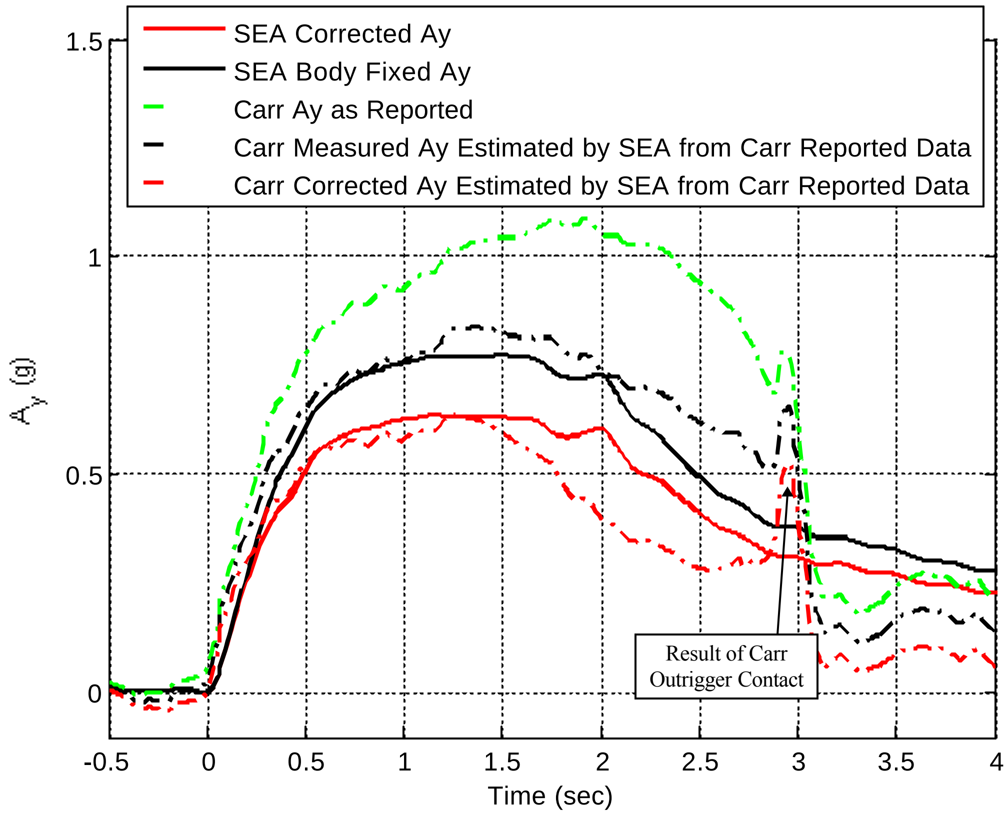
The following two slides contain graphs with data from S-E-A's testing shown using solid lines and data based off of Carr Engineering's reported data shown using dashed lines.

On the next slide, the solid red line shows S-E-A's ground plane lateral acceleration as measured directly by their sensor. This is same data shown in S-E-A's report for Vehicle B in the representative GVWR loading condition. The solid black line is the body-fixed lateral acceleration for the vehicle during S-E-A's test.

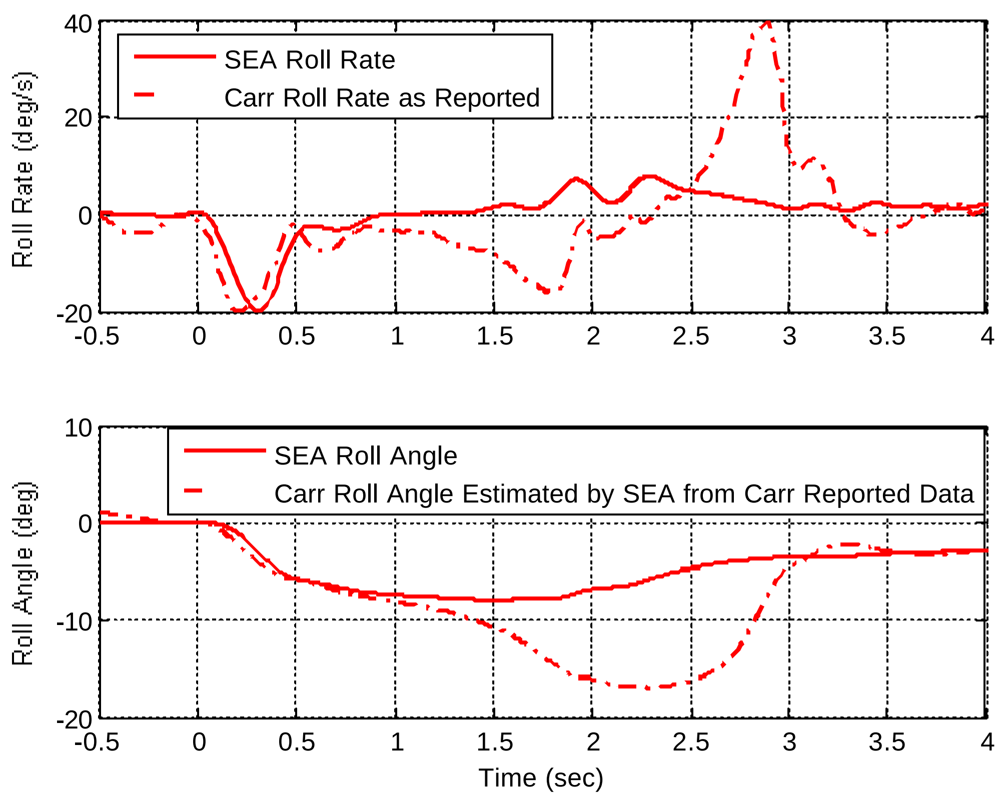
The dashed green line is the plot Carr Engineering reported for their ground plane (Corrected) lateral acceleration. Carr Engineering did not report the vehicle roll angle during this test. However, S-E-A estimated the roll angle by integrating the roll rate data presented by Carr Engineering (Slide 12). Using this estimated roll rate, S-E-A was able to estimate the curve for the Carr Engineering measured Ay using Carr Engineering's equation listed on Slide 9. The dashed black line shows the estimated Carr Engineering body-fixed lateral acceleration. Then, using the correct equation for computing ground plane (Corrected) lateral acceleration listed on Slide 7, and assuming that the measured vertical acceleration was equal to –1.0 g, S-E-A estimated the Carr Engineering ground plane (Corrected) lateral acceleration, which is plotted as the dashed red line.

Given the fact that S-E-A based their calculations for the "corrected" Carr Engineering ground plane lateral acceleration (dashed red line) by picking off data points from the hardcopy ROVHA report (and then integrating the hardcopy reported roll rate to get roll angle) and from assuming that the measured vertical acceleration during the Carr Engineering test was –1.0 g, the S-E-A ground plane lateral acceleration (solid red line) and the S-E-A estimated Carr Engineering ground plane lateral acceleration (dashed red line) through the point of two wheel lift match quite well (and the peak Ay values are very close). Certainly the differences are not were nearly as huge as the differences between the solid red line (S-E-A reported ground plane lateral acceleration) and the dashed green line (Carr Engineering ground plane lateral acceleration).

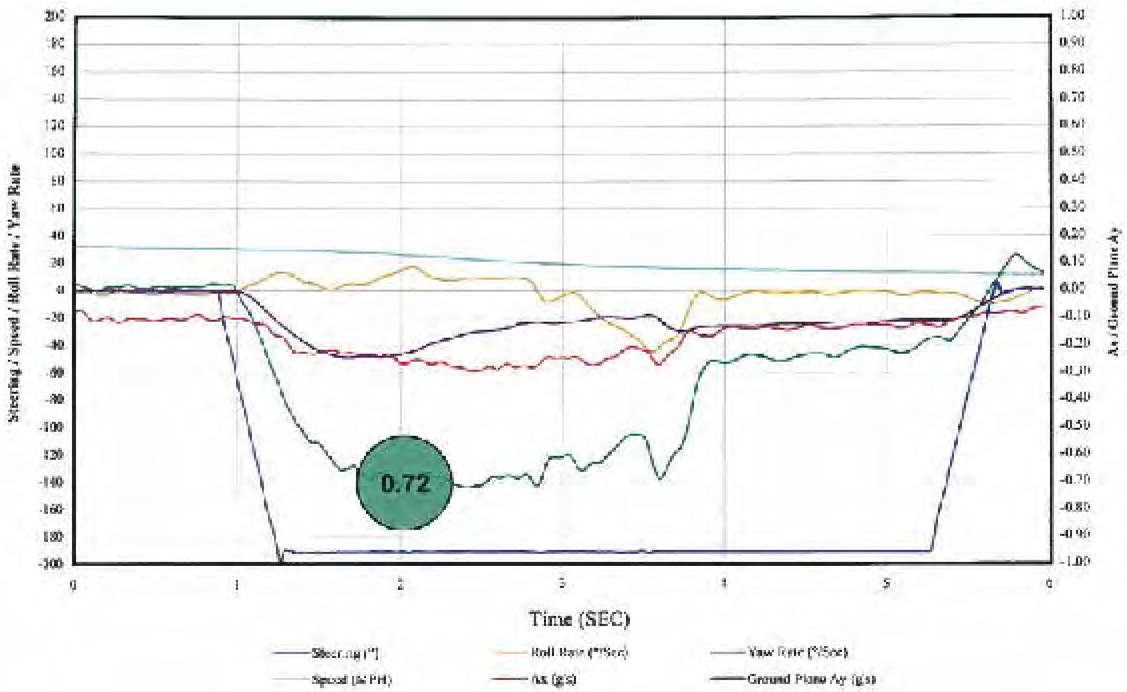
Vehicle B - GVWR Loading Condition



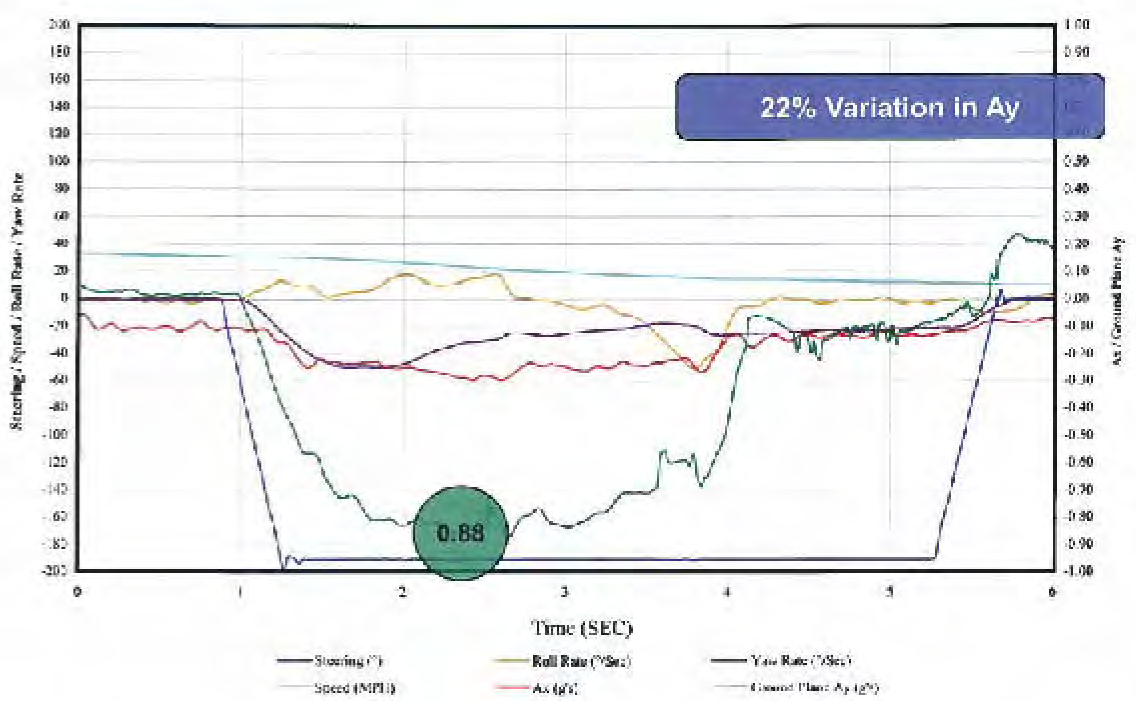
Vehicle B - GVWR Loading Condition



J-Turn Ay Variability / CEI Analysis



J-Turn Ay Variability / CEI Analysis



J-Turn Ay Variability

- OPEI calculated vehicle variation of ~19% of data range using SEA results

- CEI measured ~22% Ay test-to-test variation

Lack of adherence to exacting test methodologies and/or improper data collection or data post processing is likely the reason for this variation

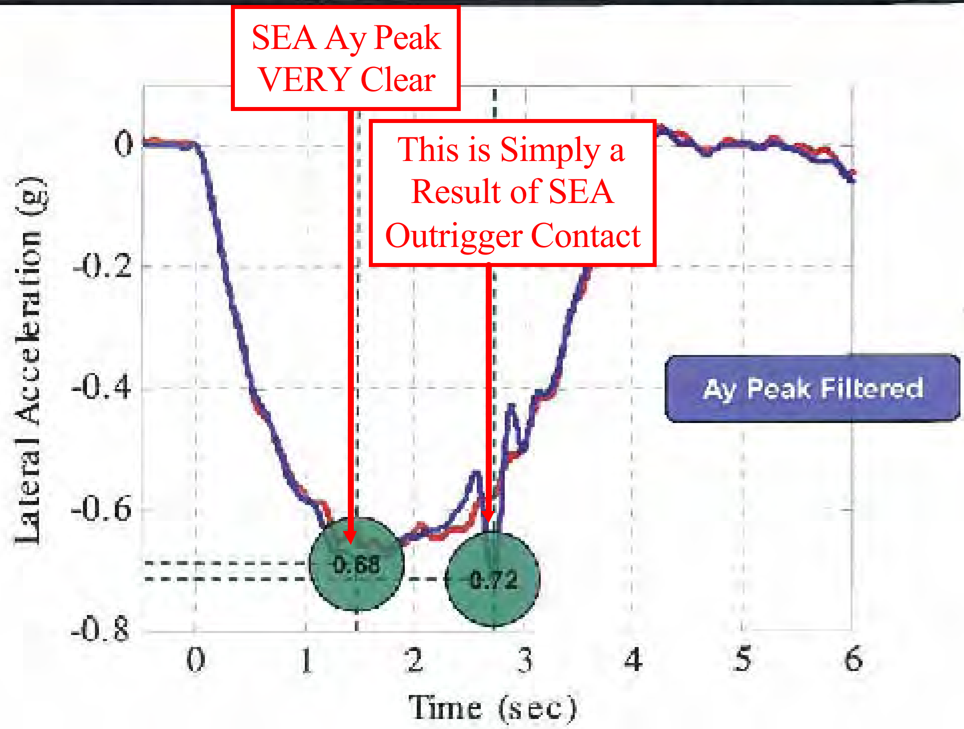
J-Turn Ay Variability

- Inconsistent results based on specific testing conditions and methodology that do not satisfy the CPSC/SEA-stated objective of being both accurate and repeatable

S-E-A had no such inconsistent results

- Inappropriate for use as a standard or metric due to large test-to-test variability

SEA J-Turn Ay Results / Vehicle G



J-Turn Ay Measurement

- **Results generated by CEI (using SEA methodology) show a wider range of rolling motions**

  Why (if same steering and same speed)?

- **Some vehicles displayed rolling motions which prevented an accurate or reliable measurement of Ay**

  Measurement of Ay or Calculation of Ay?

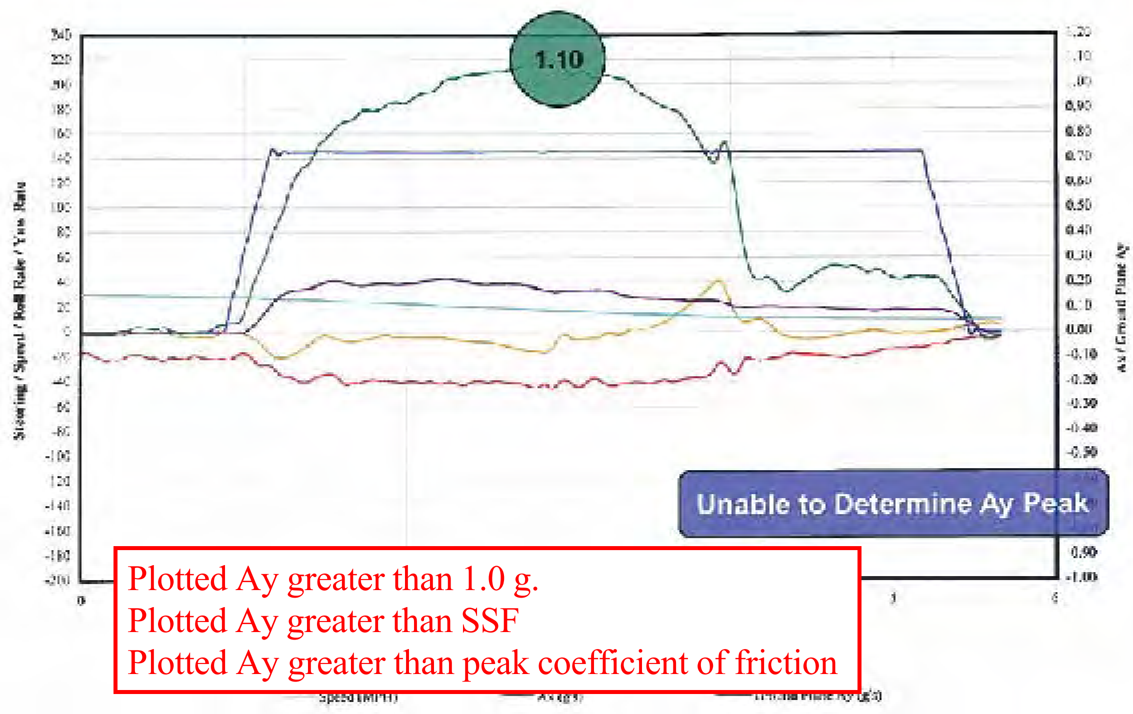
- **Ay selected by CEI as local maximum excluding transients generated**

  This was not an issue using the S-E-A data.

- **Like SEA, unknown / unquantified effect of outrigger contact during generation of local maximum**

  NO. This was not an issue using the S-E-A data.

J-Turn Ay Results / Vehicle B



Carr Engineering Reports: **Unable to Determine Ay Peak**

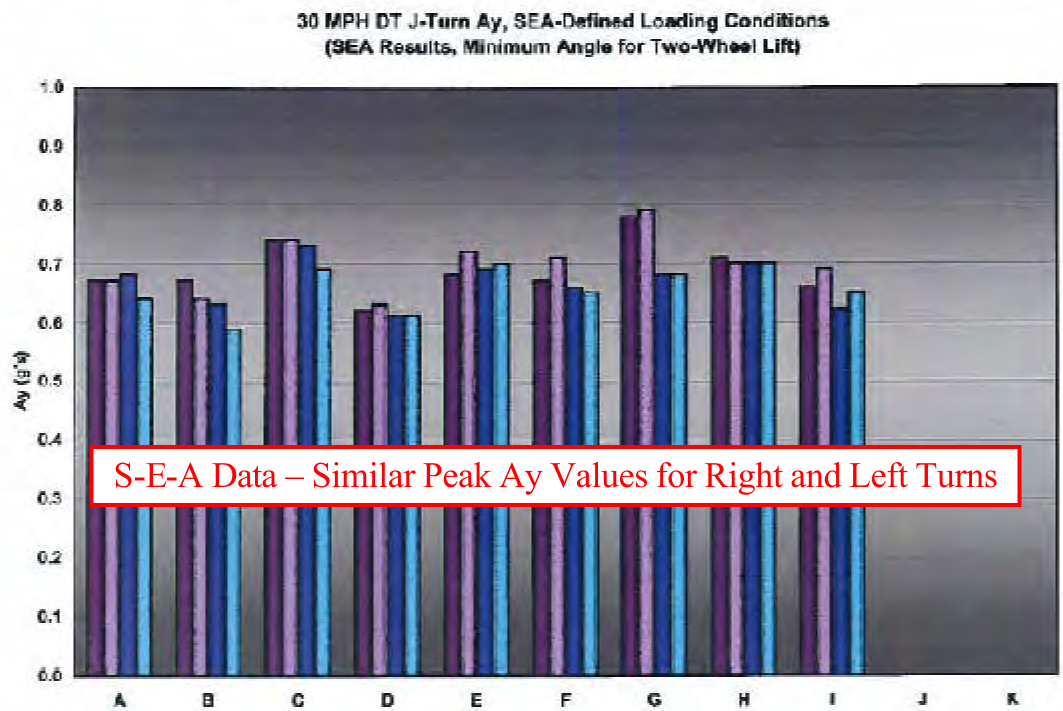
It is generally ALWAYS possible to determine Peak Ay from vehicle response data from dropped throttle J-turn tests.

S-E-A's Reports have corrected lateral acceleration plots for over 200 dropped throttle J-Turn tests. Some of these tests resulted in two-wheel lift and outrigger contact, and some did not.

For every single one of these tests, S-E-A was able to determine a peak Ay.

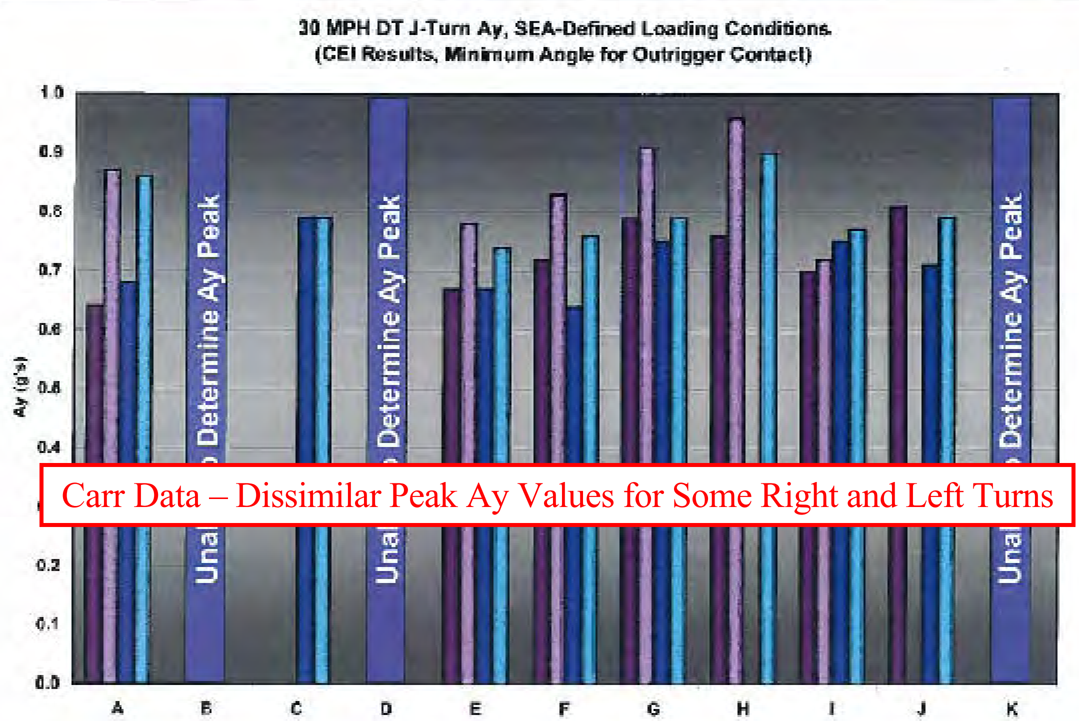
Carr Engineering's lack of adherence to exacting test methodologies and/or errors in processing their data is likely the cause of their inability to determine Ay peaks.

J-Turn Ay Results



21

J-Turn Ay Results



22

For all vehicles, all of the left turn and right turn average values for Ay peak reported by Carr Engineering are larger than those determined by S-E-A.

Carr Engineering's lack of adherence to exacting test methodologies and/or errors in processing their data is likely the reason their reported Ay peak values are higher than those determined by S-E-A.

====================

For several vehicles, Carr Engineering reported Ay peak values in left J-turns that significantly differ from those they reported in right J-turns.

S-E-A found no such large left-to-right variation in any of the vehicles they tested. It is likely that the differences reported by Carr Engineering are likely a result of their lack of adherence to exacting test methodologies and/or errors in processing their data.

Test Surface Condition Variations Can Contribute to Variations In SWA Results

S-E-A Testing Conducted
on the asphalt Vehicle Dynamics Area (VDA)
at the Transportation Research Center (TRC),
with the following measured surface properties:

Table 1: TRC Skid Number Measurements

Location	VDA	
Pad #	V-5, dry	
Pavement	Asphalt	
Surface	Untreated	
Condition	Dry	
Date	Peak PBC	Slide SN
5/5/2010	92.5	82.2
6/1/2010	98.1	84.7
6/21/2010	92.3	85.0
7/5/2010	95.7	83.2
7/19/2010	97.0	82.8
8/2/2010	98.2	84.9
8/23/2010	93.3	83.5
9/7/2010	96.6	86.5
9/27/2010	94.6	86.3
5/11/2011	92.7	85.0

Slope = 1.0%

Carr Engineering Testing Conducted
on the a concrete surface with
unreported (or unknown) surface properties.

?

Slope = ?

Concluding Comments Regarding Accuracy and Repeatability of Carr Engineering's Dropped-Throttle J-Turn Data

Carr Engineering's dropped-throttle J-turn test results did not demonstrate that S-E-A's dropped-throttle J-turn test results are either **inaccurate** or **unrepeatable**

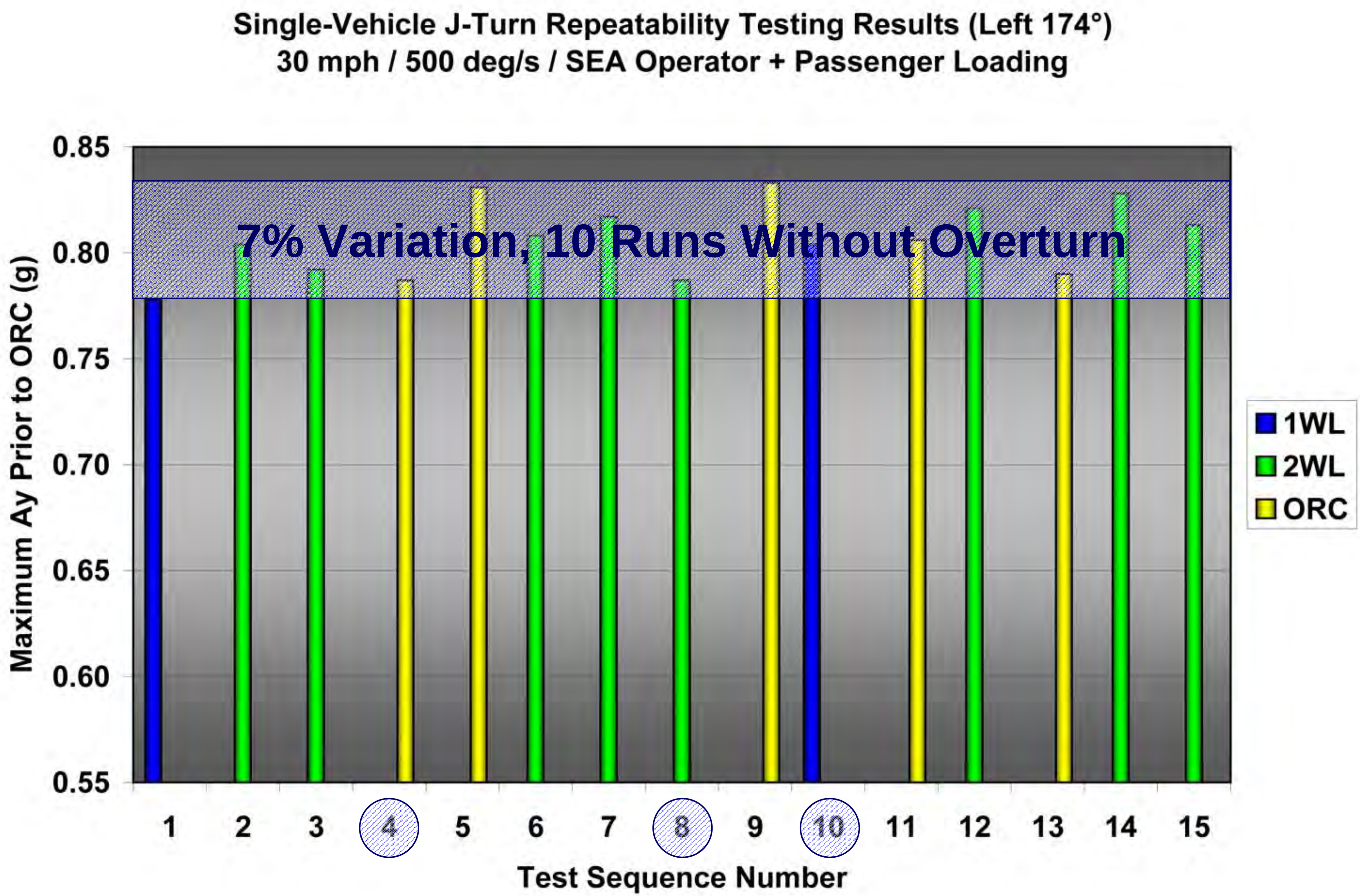
ROHVA / CPSC
Technical Discussion

July 19, 2012

Carr Engineering, Inc.

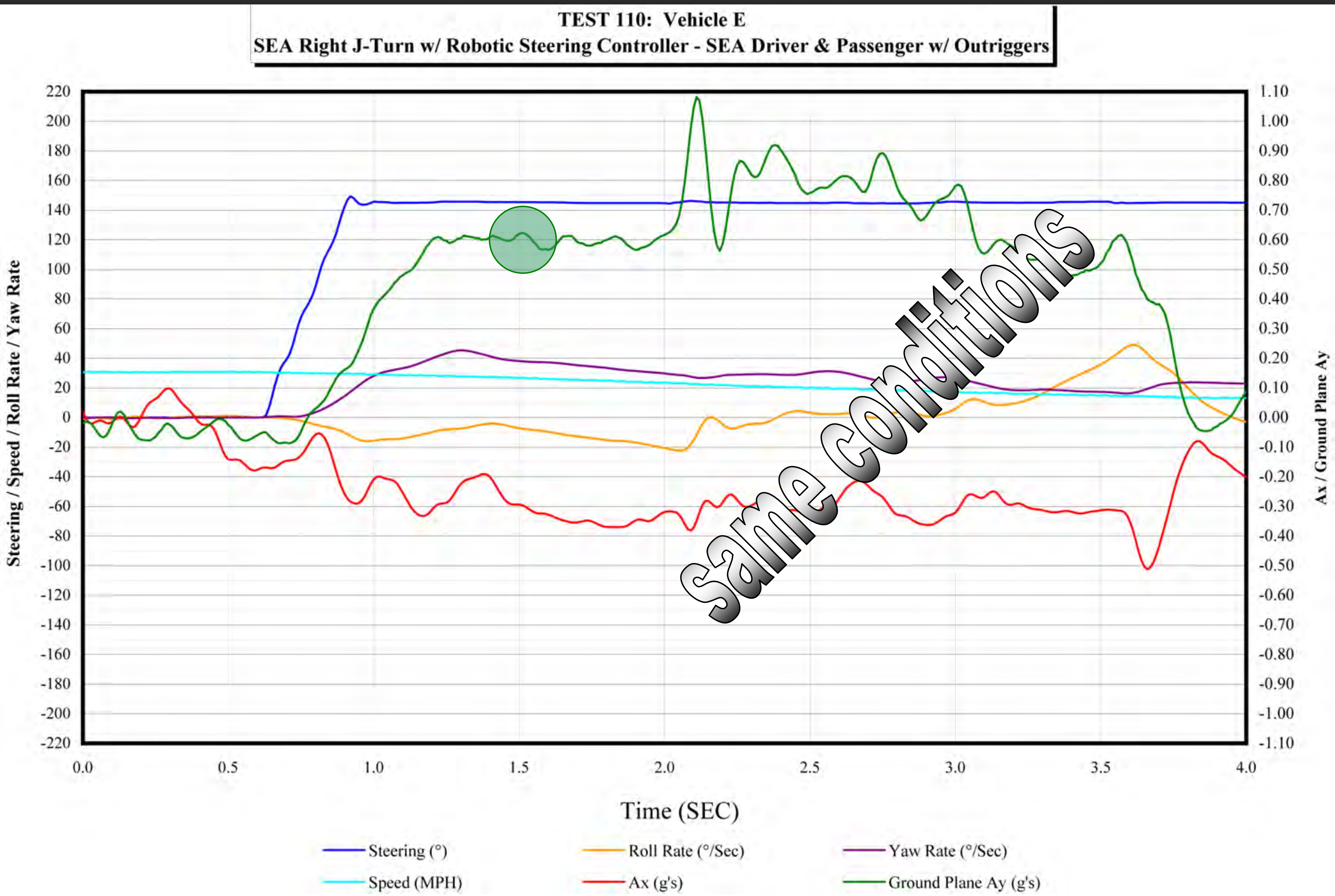
Single-Vehicle J-Turn Repeatability Study

Vehicle E

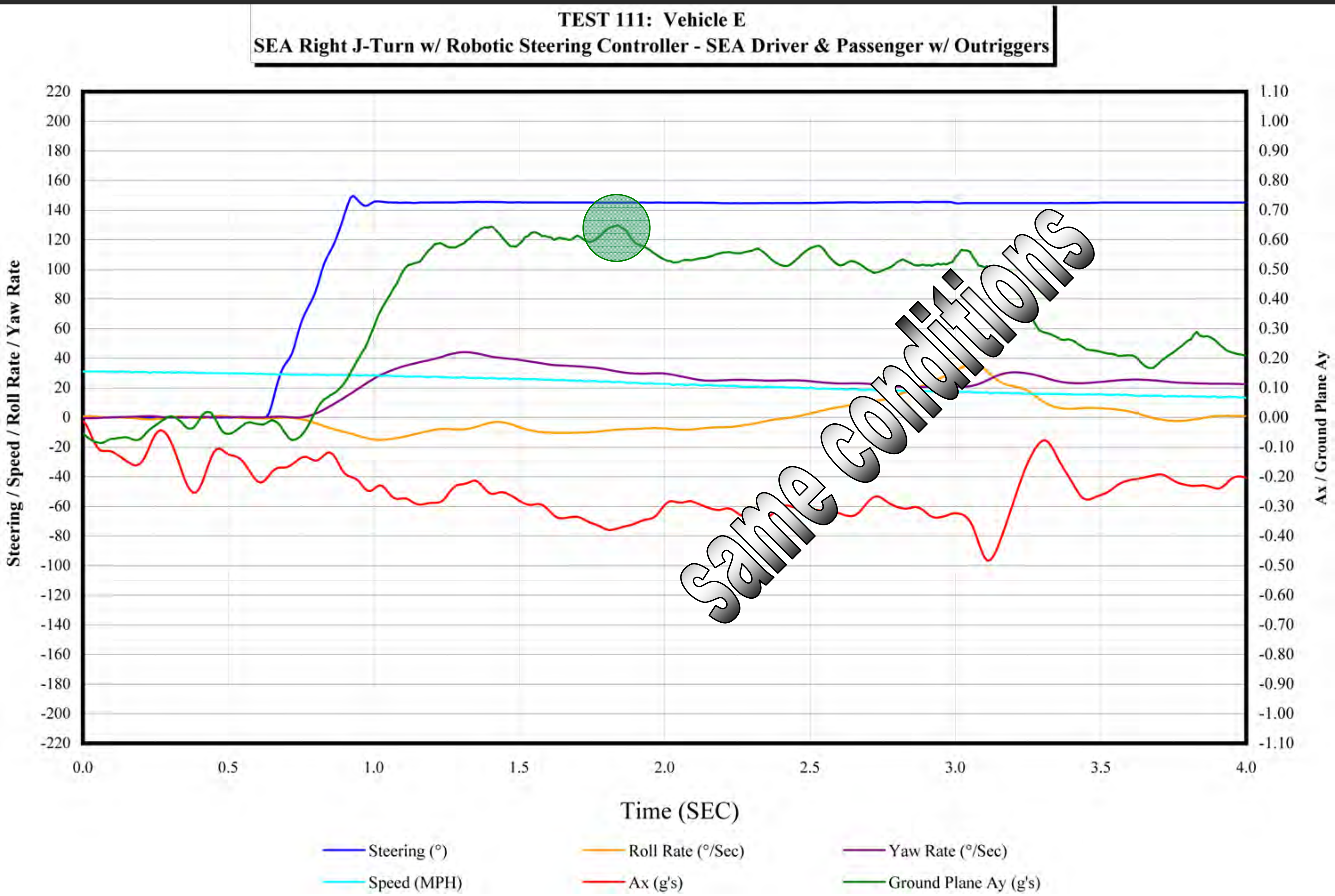


Single-Vehicle J-Turn Repeatability Testing Results (Left 174°)
30 mph / 500 deg/s / SEA Operator + Passenger Loading
7% Variation, 10 Runs Without Overturn
Maximum Ay Prior to ORC (g)
0.85
0.80
0.75
0.70
0.65
0.60
0.55
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Test Sequence Number
1WL
2WL
ORC

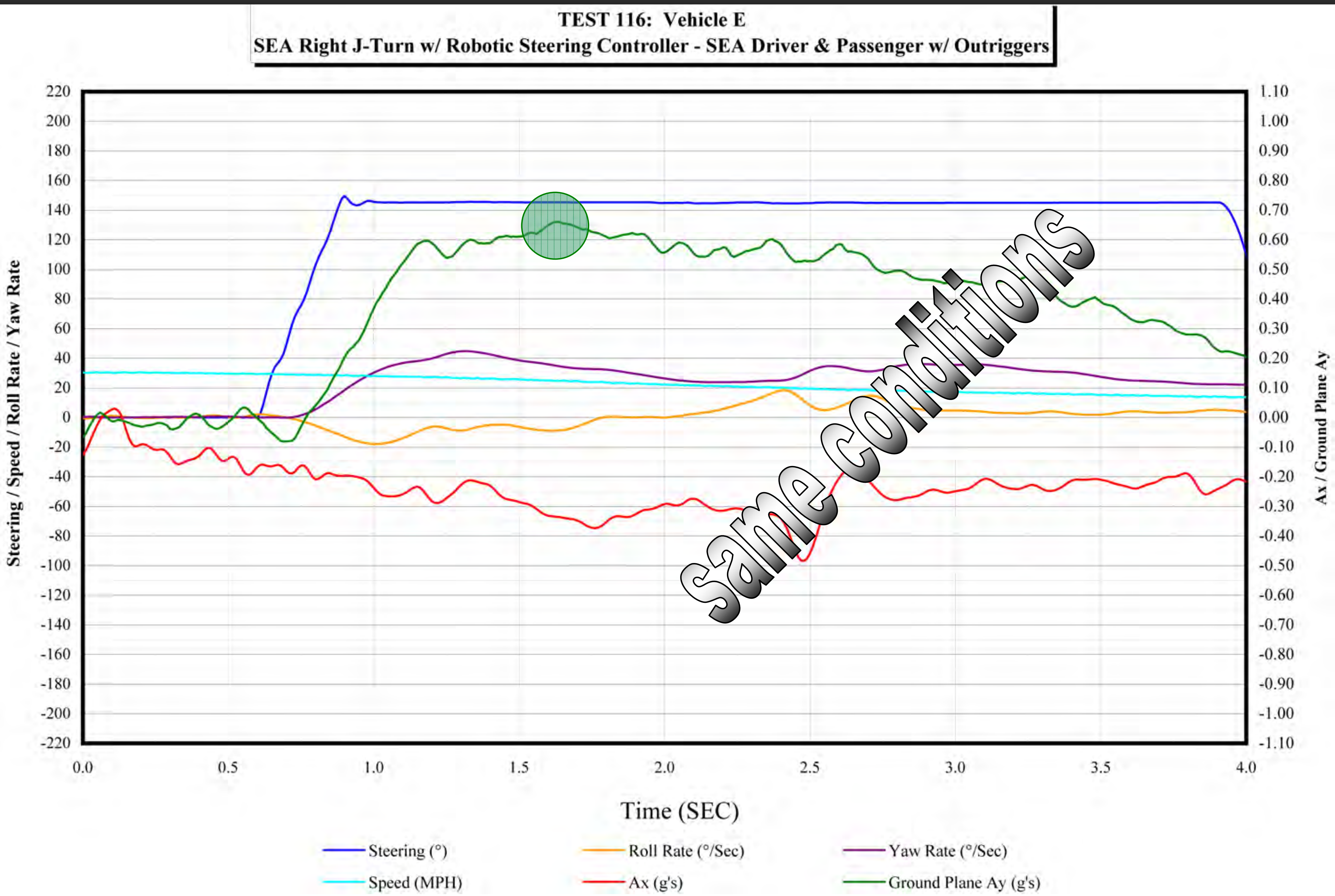
0.623 g w/ Outrigger Contact



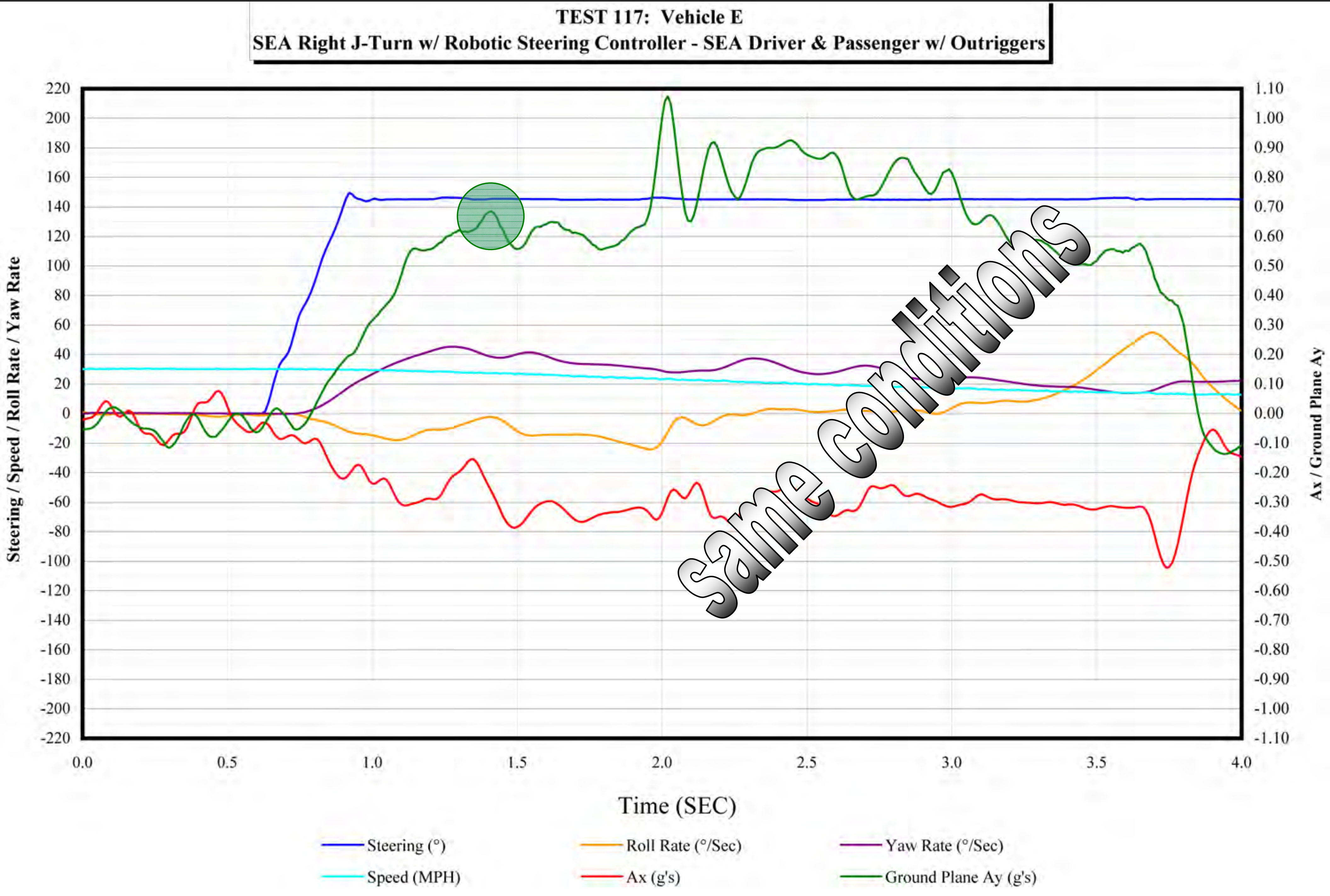
0.649 g w/ Two-Wheel Lift



0.660 g w/ One-Wheel Lift

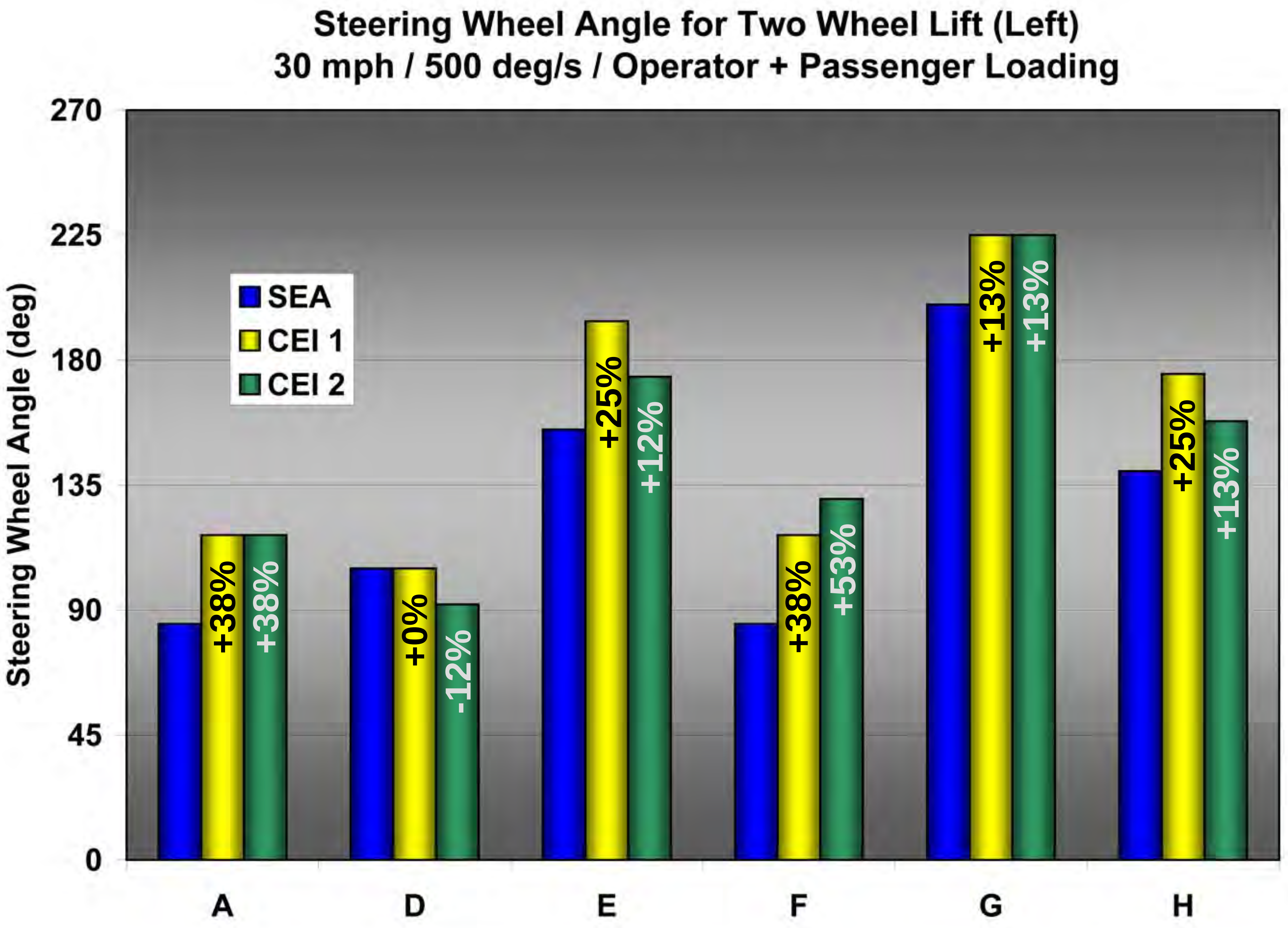


0.685 g w/ Outrigger Contact

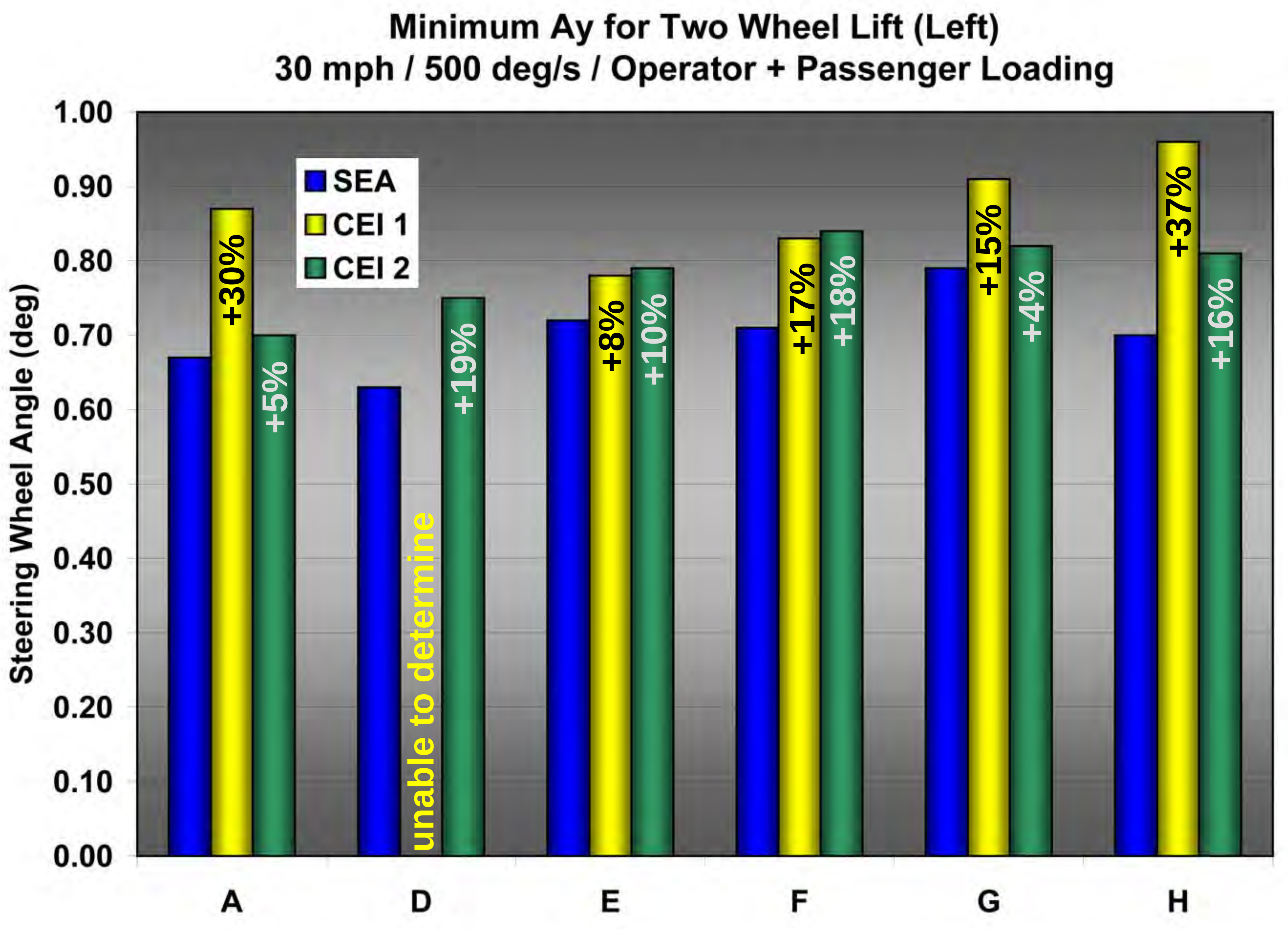


Multi-Vehicle J-Turn Repeatability Study

SWA Results and Analysis



Ay Results and Analysis



CPSC Responses to ROHVA Questions

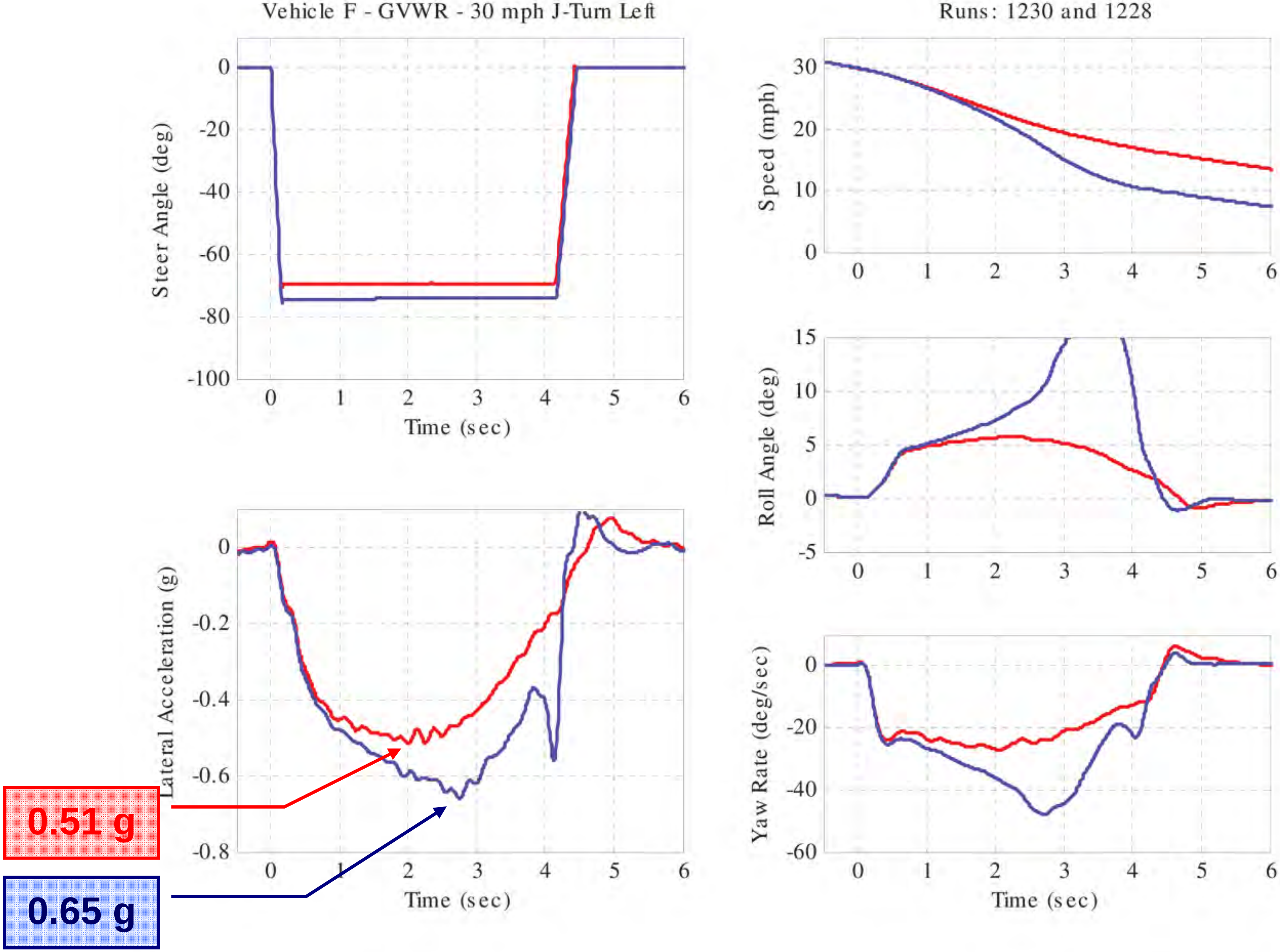
ROHVA Question 4

- **Q: A review of the dropped throttle J-turn testing for which results are presented in Appendix E of both the April and August 2011 SEA Reports indicates that data from several tests may not have been included in the original Reports. In addition to the runs numbered 116 and 117, 1128 and 1129, and 1326 and 1328, were there any other tests performed where a vehicle (or vehicles) in the operator and passenger loading configuration showed an Ay variability of 0.03 g or greater between runs when tested in the same direction? If so, please list the machine(s) by identifying letter and provide the test results for all such runs.**

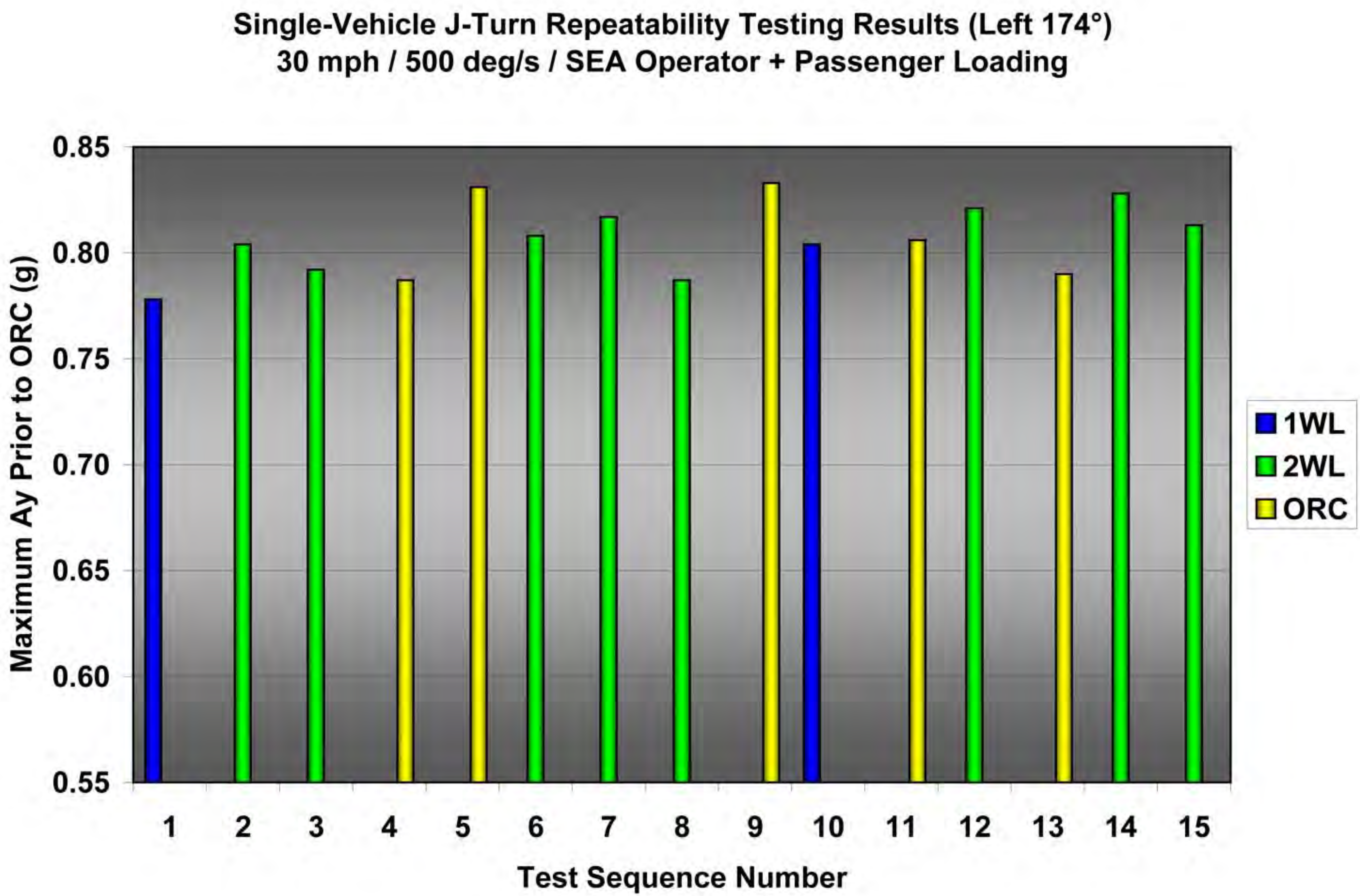
CPSC Response – Question 4

- **A: In Section 4.5 of the April 2011 report SEA states: "...the blue lines are the tests with the minimum steering that resulted in tip-up and the red lines are the tests with the maximum steering that did not result in tip-up." There are no tests with intermediate steering or severity between these two. These blue and red lines are shown for all vehicles in both the right and left steer directions.**

SEA Data – Vehicle F



Vehicle E



Single-Vehicle J-Turn Repeatability Testing Results (Left 174°)
30 mph / 500 deg/s / SEA Operator + Passenger Loading
Maximum Ay Prior to ORC (g)
0.85
0.80
0.75
0.70
0.65
0.60
0.55
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Test Sequence Number
1WL
2WL
ORC

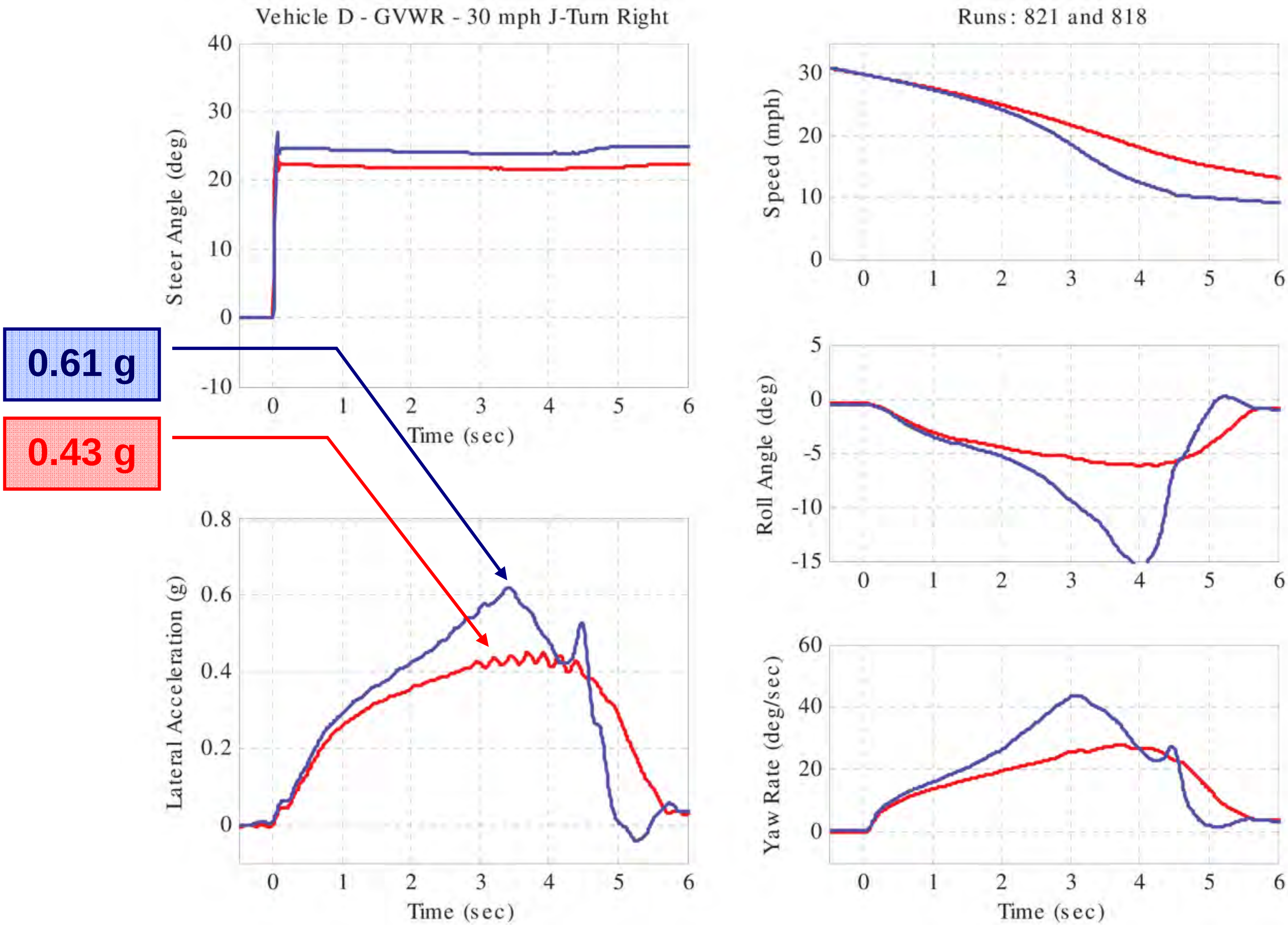
ROHVA Question 6

- Q: From page 12 of the SEA report, ROHVA understands that "…tip-up events are considered those that produced significant two-wheel lift and in almost all cases outrigger contact." Please identify the number of drop throttle J-Turn tests performed by SEA where 2-wheel lift was observed without outrigger contact. Please provide this data, by machine, for both loading conditions tested. If the precise number of runs cannot be provided, please provide an approximate anecdotal answer rounding to the nearest 10%.

CPSC Response – Question 6

- **The statement "For this testing, tip-up events are considered those that produced significant two-wheel lift and in almost all cases outrigger contact," is describing that the lateral threshold testing of these vehicles resulted in two-wheel lift that would have continued into a 90 degree rollover if the outrigger did not prevent the rollover event from occurring. Therefore, to determine the minimum lateral acceleration required to induce rollover, the tests were repeated at smaller and smaller steer angles until the vehicle exhibited just enough two-wheel lift to measure that minimum lateral acceleration but not enough to make outrigger contact (and thereby incorrectly measure the lateral acceleration caused by outrigger impact with the ground). 100% of the J-Turn tests that measured the minimum lateral acceleration of the vehicle at rollover threshold exhibited 2-wheel lift without outrigger contact since by definition that was how the value was measured.**

SEA Data – Vehicle D

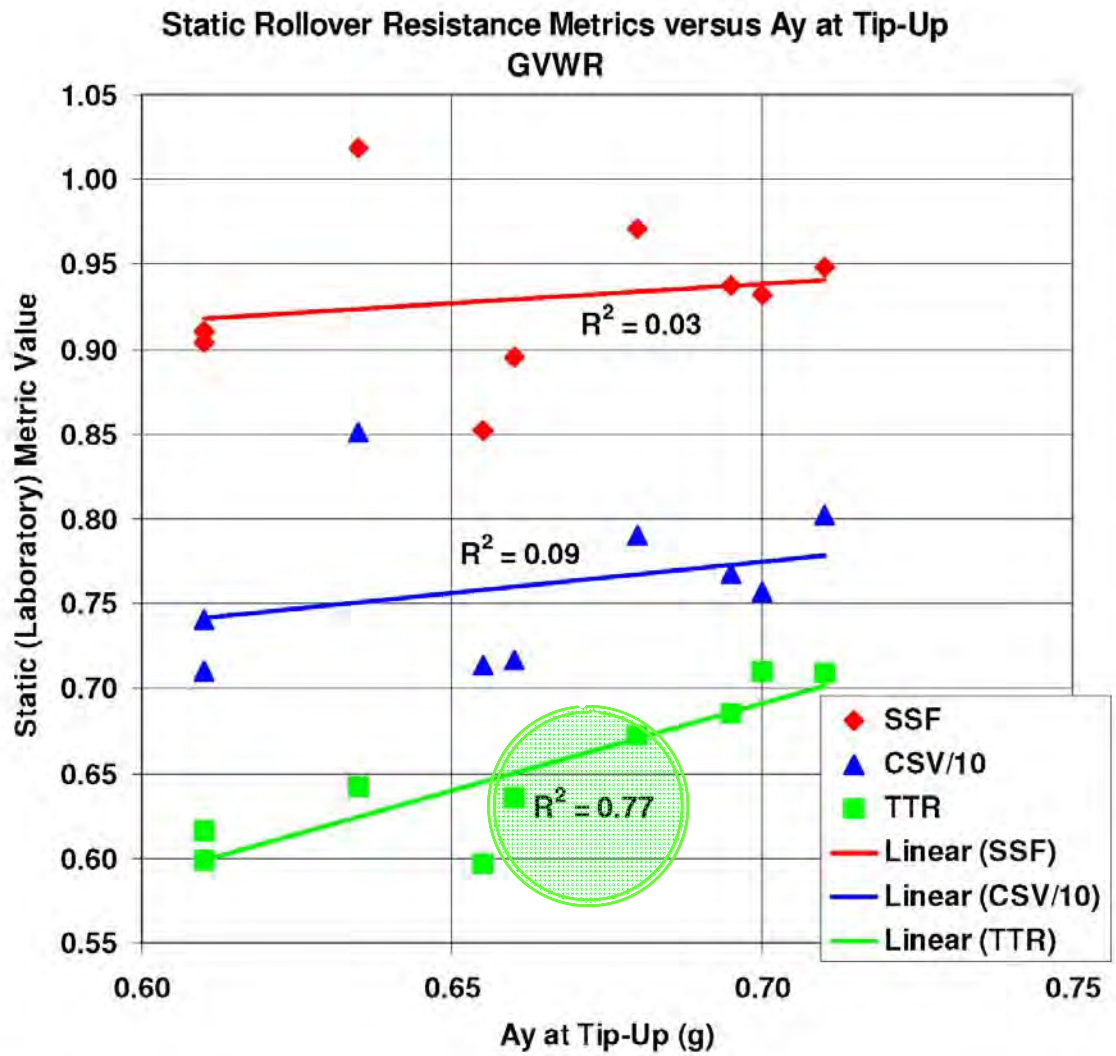


SEA Data – Vehicle D

Maximum Lateral Accelerations During Dropped Throttle J-Turns Vehicle D – GVWR Loading						
	Right Steer Maneuvers		Left Steer Maneuvers		Average of Right and Left Maneuvers	
Percentage of Steering Required for Two Wheel Lift (%)	Steering Angle (deg)	Lateral Accel. (g)	Steering Angle (deg)	Lateral Accel. (g)	Steering Angle (deg)	Lateral Accel. (g)
0.0	0.0	0.00	0.0	0.00	0.0	0.000
25.0	6.3	0.09	-6.9	-0.10	6.6	0.095
50.0	12.5	0.17	-13.8	-0.21	13.1	0.190
75.0	18.8	0.26	-20.6	-0.37	19.7	0.315
87.5	21.9	0.48	-24.1	-0.54	23.0	0.510
100.0	25.0	0.61	-27.5	-0.61	26.3	0.610

Understeer Correlation Study

SEA Report Correlation Analysis

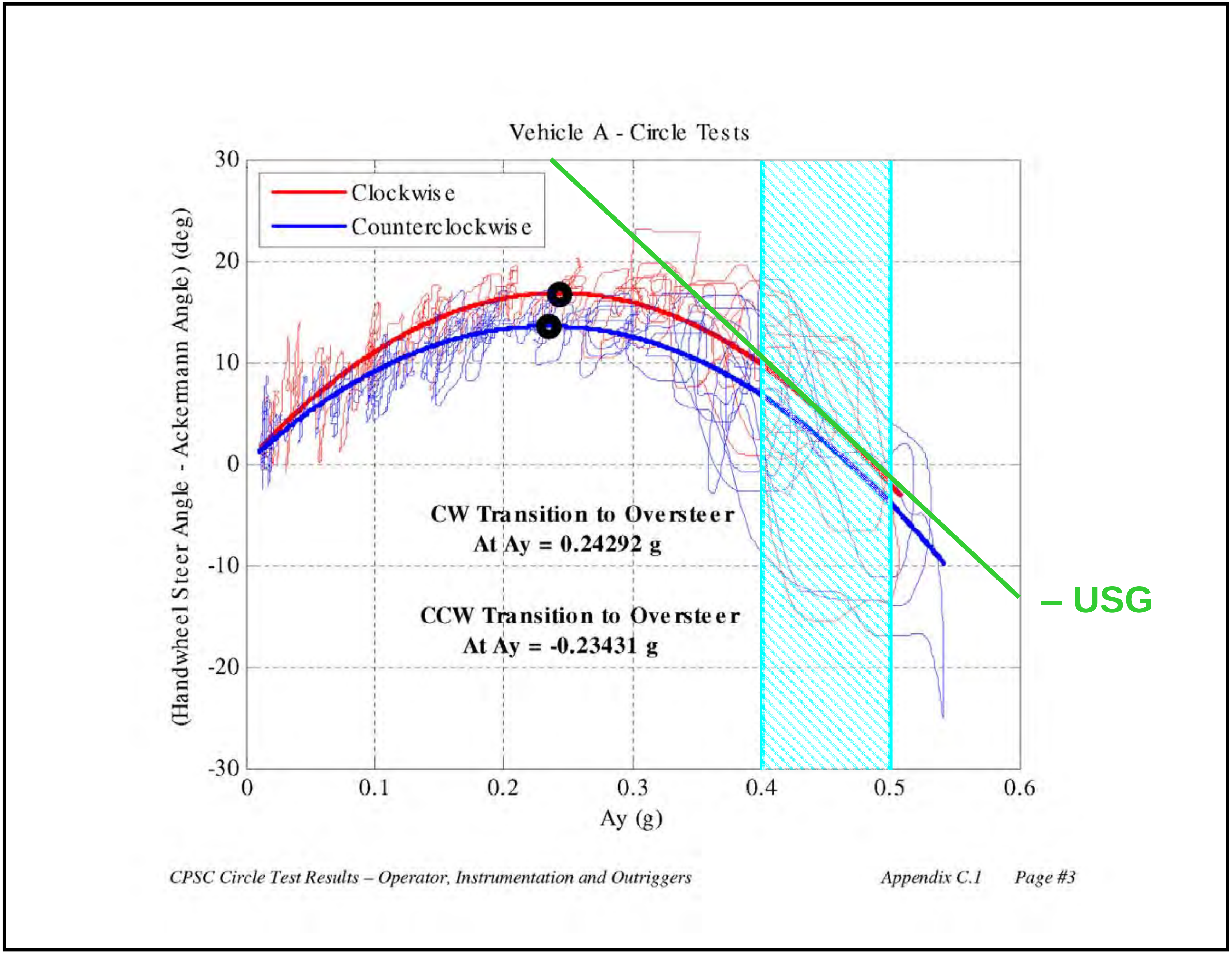


CPSC Test Results – Summary Bar Charts, Graphs, and Tables *Appendix B* *Page #58*

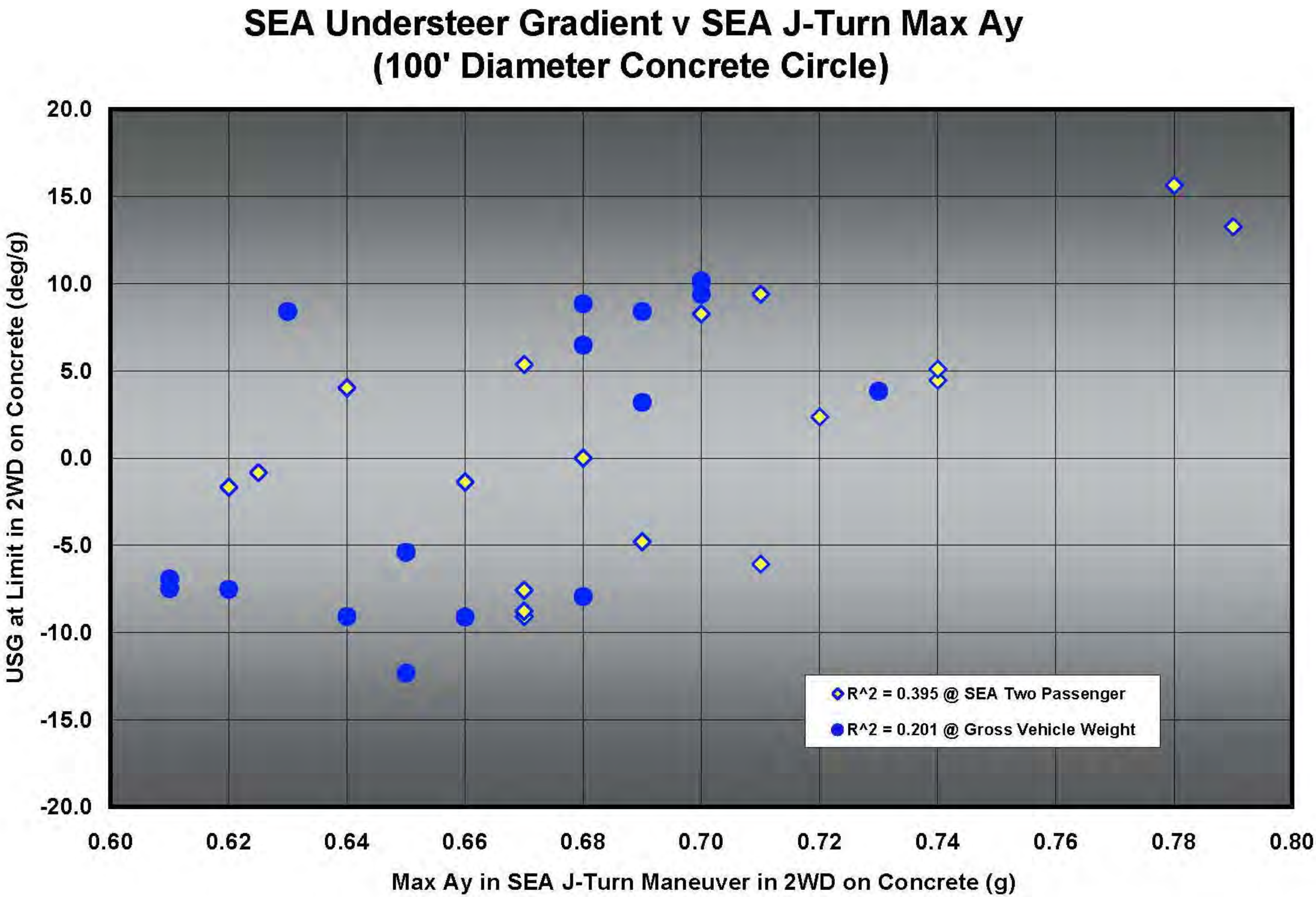
SEA Report Correlation Analysis

Pages 44 and 45 (Operator and Passenger) and Pages 57 and 58 (GVWR) contain exhibits comparing the laboratory rollover resistance metrics to the lateral accelerations required for tip-ups in the dropped throttle J-turns. Pages 44 and 57 are bar charts of the values, while Pages 45 and 58 are graphs with plots of the rollover resistance metrics versus lateral acceleration at tip-up. Linear fits of the plots are also provided on the graphs. The graphs on Pages 45 and 58 indicate that TTR has a better correlation to lateral acceleration at tip-up than do SSF or CSV. However, none of the static metrics examined correlated very well with the minimum lateral acceleration thresholds. The data for Vehicle I, the four-passenger vehicle, has the biggest outliers from the linear fits for SSF and CSV in both loading configurations.

Quantification of USG



USG Correlation on Concrete

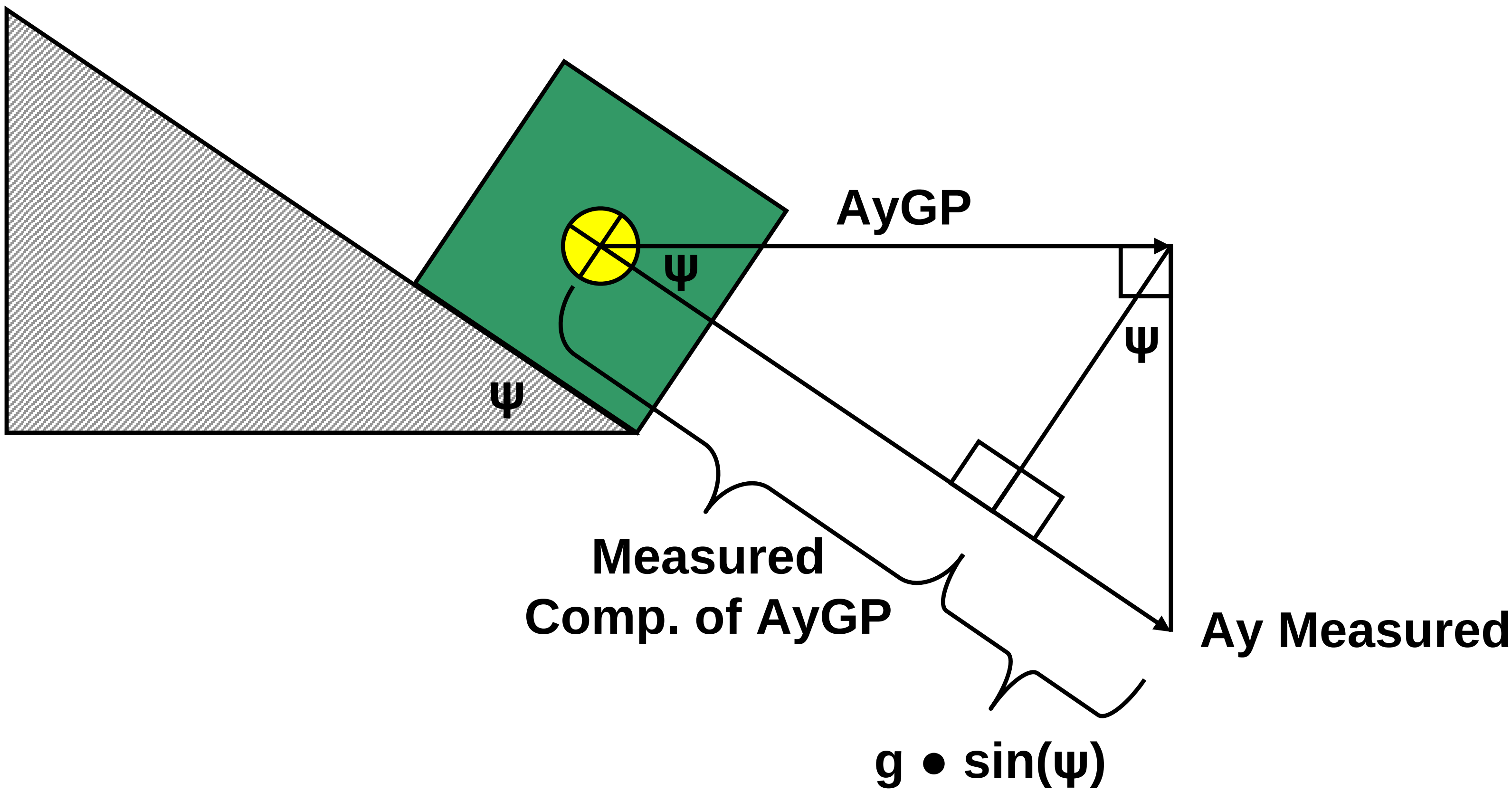


USG Correlation Summary

	SEA Two Passenger	SEA GVW Loading
USG (Concrete) v. SEA Max Ay	0.40	0.20
USG (Concrete) v. SEA TTA	0.27	0.40
USG (Concrete) v. SEA SSF	0.23	0.02
USG (Dirt) v. SEA Max Ay	0.00	0.04
USG (Dirt) v. SEA TTA	0.01	0.07
USG (Dirt) v. SEA SSF	0.07	0.01

Ay Body Roll Correction Factor

Ay Body Roll Correction Factor



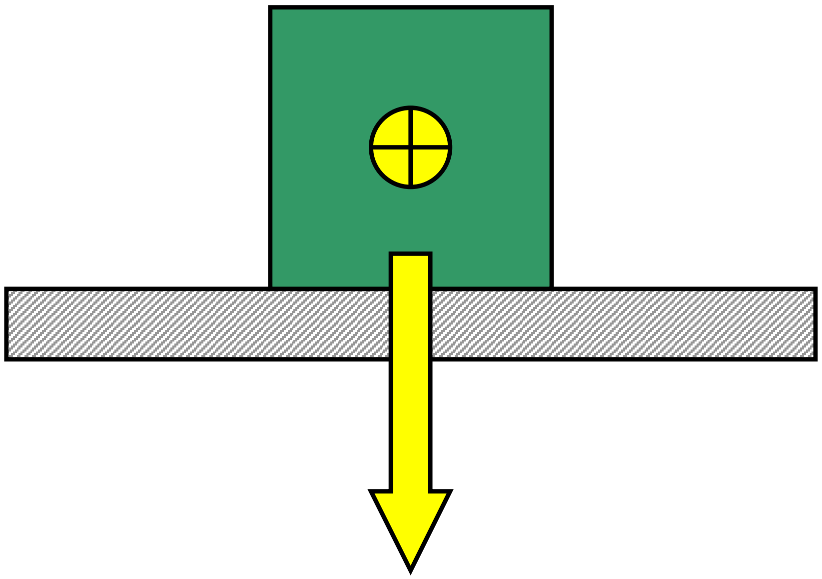
1. Measured Comp. of AyGP = (AyGP • cos(ψ))

2. Ay Measured = (AyGP • cos(ψ)) + (g • sin(ψ))

3. AyGP = (Ay Measured - sin(ψ)) / (cos(ψ)) in units of g

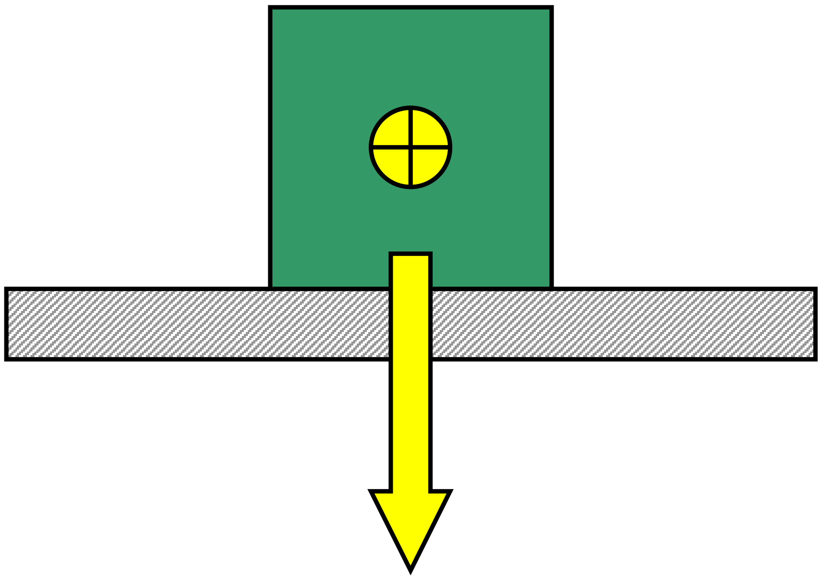
Ay Body Roll Correction Factor

$(Ay \bullet \cos(\psi)) - (Az \bullet \sin(\psi))$



1.0 g convention

$(Ay - \sin(\psi)) / (\cos(\psi))$



0.0 g convention

49 CFR Part 563 – EDR

- **"Delphi recommended that NHTSA provide greater specificity in the definition of 0 G normal acceleration, because the term 0 G is used inconsistently within the industry (e.g., 0 G is sometimes normalized for the 1 G bias due to gravity). We agree with Delphi's comments and have revised the definition."**