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Braking and Swerving Capabilities of Three-Wheeled Motorcycles

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Abstract

This paper reports testing and analysis of the braking and swerving capabilities of on-road, three-wheeled motorcycles. A three-wheeled vehicle has handling and stability characteristics that differ both from two-wheeled motorcycles and from four-wheeled vehicles. The data reported in this paper will enable accident reconstructionists to consider these different characteristics when analyzing a three-wheeled motorcycle operator's ability to brake or swerve to avoid a crash. The testing in this study utilized two riders operating two Harley-Davidson Tri-Glide motorcycles with two wheels in the rear and one in the front. Testing was also conducted with ballast to explore the influence of passenger or cargo weight.

Numerous studies have documented the braking capabilities of two-wheeled motorcycles with riders of varying skill levels and with a range of braking systems. The results reported here showed that when both the front and rear brakes are utilized, the decelerations produced during braking are consistent with, but in the upper half of, the range of decelerations previously reported for two-wheeled motorcycles. Studies of two-wheeled motorcycles commonly report that most of the deceleration is produced through use of the front brake. The testing reported here showed that the rear brake produced most of the deceleration for the three-wheeled motorcycles used in the testing. In relationship to swerving, this paper examines the accuracy of a commonly-used formula for calculating the longitudinal distance necessary for a swerve of a specified lateral distance. The results showed that, with a modification to the coefficient of this equation, this formula can be used to reasonably estimate the distance necessary for a three-wheeled motorcycle to swerve.

Introduction

This study explores the braking and swerving capabilities of three-wheeled motorcycles. These motorcycles have recently seen a surge in popularity.[1,2] Several reasons might explain this. Baby boomers make up a large, aging population that still want to ride, but prefer the comfort of the three-wheeled motorcycle to the more physically demanding requirements of the typical heavy touring motorcycle.[3] Also, both new riders and veteran riders might prefer the stability of three wheels to the counter steering techniques required to maneuver a motorcycle. Some three-wheeled motorcycles also provide additional hauling and carrying capacities than comparable two-wheeled motorcycles. Three-wheeled motorcycles also provide the open-air riding experience for those with physical disabilities, who may have difficulty balancing and controlling a vehicle with only two wheels.

Harley-Davidson began manufacturing a three-wheeled motorcycle called the Servi-Car in 1932 (Figure 1). This motorcycle was discontinued in 1975 and Harley-Davidson did not begin making another three-wheeled motorcycle until the Tri Glide Ultra Classic in 2009. In addition to Harley-Davidson, Can-Am, Polaris, and Honda now manufacture three-wheeled motorcycles. Some of these motorcycles have two wheels in the back and on in the front and some have two

FIGURE 1 Harley-Davidson Servi-Car

1 https://triblive.com/business/headlines/7531135-74/harley-motorcycle-glide.
2 https://rapidcityjournal.com/sturgisrallydaily/trikes-popularity-and-sales-continue-to-climb/article_4418d3d0-bfc6-11e0-969d-001cc4c002e0.html.
3 NY Times, "Born to Be Wild, Aging Bikers Settle for Comfy," September 14, 2012.

wheels in the front and one in the back. The Can-Am Spyder depicted in Figure 2 is an example of a three-wheeled motorcycle with two wheels in the front. The motorcycles tested in this study had two wheels in the back and it should be acknowledged that some of the results reported here may not apply to three-wheeled motorcycles with two wheels in the front. The various three-wheeled motorcycles also likely have differences in their braking systems that will influence their braking and swerving characteristics. Some companies, such as Champion Trikes and Side Cars, also make conversion kits for larger motorcycles manufactured by Honda, Victory, Indian, Kawasaki, and Harley-Davidson. These modified two-wheeled motorcycles may also have handling characteristics that are not captured by the testing reported in this paper.

Braking

Numerous studies have documented the braking capabilities of two-wheeled motorcycles with riders of varying skill levels and with a range of braking systems [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Table 1 summarizes the results from 10 of these studies. Because motorcycles with conventional braking systems require the operator to independently control the front and rear brakes, most of these studies have examined differences in the deceleration achieved with the rear brake only, with the front brake only, and with combined use of the front and rear brakes.

These studies have shown that the maximum deceleration for two-wheeled motorcycles with conventional braking systems is achieved with combined application of the front and rear brakes, although the decelerations achieved with the front brake alone are nearly as high as those generated with both brakes. Decelerations generated with use of the rear brake only are consistently lower than those generated with the front brake or with both brakes. This is the case because, during heavy braking, a significant portion of the weight of the motorcycle and rider shift to the front wheel of the motorcycle. This results in the available traction at the front wheel being significantly higher than the available traction at the rear wheel.

For a three-wheeled motorcycle with two wheels in the rear, a greater percentage of the motorcycle's weight is carried by the rear wheels and the weight transfer to the front of the motorcycle during braking is less significant than for a two-wheeled motorcycle. This changes the characteristics of the deceleration when an operator uses only the front brake or only the rear brake. The testing in this paper explores the significance of these differences.

Optimal braking of a two-wheeled motorcycle without antilock brakes (ABS) occurs when the operator can modulate the brake pressure throughout the braking process to maintain the pressure at a level just below what would be necessary to lock either wheel. Many riders lack the skill to vary their level of braking pressure as weight shifts during the braking process and they may lock either the rear or front wheel. If the operator locks the front wheel and does not quickly release the front brake, the front wheel will lose traction and the motorcycle is likely to capsize (fall down). An operator can lock the rear wheel and maintain rear brake pressure without capsizing. With rear wheel lock, there is a risk that the rider will release the brake at a time when the rear wheel is not aligned with the front. This can result in a high-side fall of the motorcycle.

High-side falls typically occur when the longitudinal force at the rear tire consumes the available traction, leaving insufficient traction for maintaining lateral stability. The rear wheel can begin to slide laterally and the motorcycle can

FIGURE 2 Can-Am Spyder with Two Wheels in the Front and One in the Back.

TABLE 1 Best Effort Braking Decelerations for Two-Wheeled Motorcycles on Dry Roadways (g)

Study	Rear Brake Only (No ABS)	Front Brake Only (No ABS)	Front and Rear Combined (No ABS)	Front and Rear with ABS
Tolhurst and McKnight [1]		0.764	0.935	
Fries, Smith, and Cronrath [2]	0.31 to 0.52		0.54 to 0.88	
Hunter [3]	0.35 to 0.36	0.64 to 0.74	0.63 to 0.96	
Bartlett [4]	0.38 to 0.46	0.88 to 0.89	0.96	
Ecker [5]			0.63 ± 0.12	
Vavryn [6]			0.67	0.8
Bartlett, Baxter, Robar [7]	0.37 ± 0.06	0.60 ± 0.16	0.74 ± 0.15	
Anderson, Baxter, Robar [8]	0.42	0.65	0.71	0.93
Dunn, et al. [9]	0.345 to 0.386	0.518 to 0.709	0.612 to 0.708	0.642 to 0.842
Peck and Deyerl [10]	0.321 to 0.341			
Summary (min to max)	0.31 to 0.52	0.52 to 0.89	0.54 to 0.96	0.64 to 0.842

develop a yaw rotation. If this occurs, the motorcycle and rider will begin to lean away from the direction of travel. If the rider then releases the rear brake while this is occurring, then the longitudinal force at the rear wheel will decrease rapidly and result in a sudden increase in the available lateral traction. This can lead to the motorcycle and rider rolling to the opposite direction of the initial lean. The rider is then projected upward and thrown ahead of the motorcycle.

For a three-wheeled motorcycle, there is less risk of capsizing or of the rider experiencing a high-side fall if the they lock either the front or rear wheels. A rider can achieve a significant, if not optimal, level of deceleration by simply applying the brakes with sufficient force to lock the wheels. This means that operators of three-wheeled motorcycles require less skill to achieve a high level of deceleration than operators of two-wheeled motorcycles. Most of the maximal braking tests reported in this paper involved locked wheel braking with skid marks being deposited.

Swerving

In some situations, a motorcyclist may move laterally to avoid a hazard. Such a maneuver could be characterized as a lane change, a swerve, or a turn-away. A *lane change* is defined as a complete lateral move by a vehicle from one lane to another. The term *swerve* refers to a maneuver that is like a lane change in the sense that it involves a complete lateral movement, but it is not referenced to any marking on the roadway and will typically be smaller laterally and quicker than a lane change. Swerves are also sometimes distinguished from lane changes by the magnitude of the lateral accelerations that a driver uses [11]. Daily, Shigemura, and Daily [12] define swerves as having average lateral accelerations greater than 0.2 g. The term *turn-away* is defined as half of a swerve.

For the operator of a two-wheeled motorcycle, completing a swerve to the left would involve an initial rightward countersteer and a lean of the motorcycle to the left, followed by a leftward countersteer and lean to the right, before returning to an upright position. Steering of a three-wheeled motorcycle is not accomplished via countersteering and lean since the two rear wheels prevent the motorcycle from leaning under most conditions. A leftward swerve of a three-wheeled motorcycle would involve an initial leftward steer, followed by a rightward steer to bring the motorcycle back to its initial travel direction.

Daily, Shigemura, and Daily [12] presented the following equation for calculating the distance required for a swerve or lane change. In this equation, S is the vehicle speed in mph, L is half the lateral distance of the swerve in ft, f_y is the average lateral acceleration in gravitational units, and d_{swerve} is the longitudinal distance required for the maneuver.

$$d_{swerve} = 0.732 \cdot S \sqrt{\frac{L}{f_y}} \tag{1}$$

This equation assumes a constant speed and a circular path for each segment of the swerve. The coefficient of 0.732 in Equation (1) arises through the unit conversions that have been employed in the equation, which allow the reconstructionist to enter the inconsistent, but convenient units of mph, feet, and g's. This equation can be compared to empirical data, and if necessary, the coefficient can be modified to achieve a better fit with the data. This equation could be applied to any non-articulated vehicle, but different vehicle types could have different coefficients that would result in the best fit to empirical data.

For passenger cars, Reference 11 reported that the Daily formula calculated "the lane change time and longitudinal distance with nominally zero average percentage difference, and a standard deviation of about 5%. It is noted that although the Daily formula accurately predicts the lane change distance and time if the average acceleration is known, it does not accurately model the travel path, peak acceleration, or the acceleration profile. Due to the constant turn radius model, the vehicle path may deviate as much as about 30% at the quarter point of the full lane change maneuver. It is also noted that the Daily formula is likely not accurate if peak or threshold values are used."

Rose and Neale [13] have described the application of Equation (1) to swerve maneuvers of two-wheeled motorcycles. Past literature that has reported swerve tests of two-wheeled motorcycles has not reported measured lateral accelerations of the motorcycles [14, 15, 16]. Rose and Neale applied Equation (1) to two-wheeled motorcycles by calculating apparent lateral accelerations for previously reported two-wheeled motorcycle swerve tests. The "apparent" lateral acceleration, was the calculated lateral acceleration for which Equation (1) accurately described the maneuver. In the testing reported in this paper, lateral accelerations were measured for each swerve maneuver, and so, the applicability and accuracy of Equation (1) for swerves with three-wheeled motorcycles will be addressed directly.

Bartlett and Meyers [14] reported testing conducted with four experienced and skilled motorcyclists on two-wheeled motorcycles, swerving 2 m (6.5 ft) to their left after passing through a gate at speeds of 40 to 88 kph (25 to 55 mph). They reported the speed, distance, and time for each swerve maneuver. Unfortunately, they did not measure or calculate the lean angles (of the motorcycles or the riders) or the actual lateral accelerations utilized by the riders. They simply assumed a lateral acceleration of 0.65g and used that to propose a new empirical coefficient for Equation (1). They propose a coefficient of 0.618. In reality, it is unlikely that most riders would utilize an average lateral acceleration of 0.65g during a swerve.

The lateral acceleration of a three-wheeled motorcycle during a swerve could be limited by the willingness limits of the operator or by the lateral or roll stability limits of the vehicle. The lateral acceleration could also be limited by what is necessary for a rider to traverse the required maneuver.

Huston, Graves, and Johnson [17] presented the following equation for estimating the lateral acceleration necessary to cause a three-wheeled vehicle (with one wheel in the front and two in the rear) to begin tipping up:

$$f_{y,limit} = \frac{T_{rear}}{2h} \cdot \frac{a}{l_w} \tag{2}$$

In this equation, T_{rear} is the rear track width of the vehicle, h is the center of gravity height, a is the distance from the center of gravity to the front axle, and l_w is the wheelbase of the vehicle. This equation includes what is commonly referred to as the Static Stability Factor (SSF) - the track width divided by 2 times the center of gravity height. As with the SSF, the lateral acceleration of Equation (2) represents the minimum lateral acceleration to cause a tip-up. For a tip-up to occur at this lateral acceleration level, the lateral acceleration would have to remain at this minimum level for a sustained time. The lateral acceleration can exceed this minimum level for a short time without causing a tip-up to occur. Given this, Equation (2) may yield a reasonable estimate of the limit on *average* lateral acceleration for a swerve on a particular three-wheeled motorcycle but will not yield a reasonable estimate of the *peak* acceleration limit. See Chapter 5 in Reference 18 for a detailed discussion of the role the duration of the lateral acceleration plays in causing a tip-up.

The Bartlett and Meyers study also commented on their own testing: "The most recent testing involved relatively skilled riders who had faster transitions and greater willingness to lean than the 'average' rider generally described in the literature. Separating the perception-reaction time from the evaluation of the turn-away maneuver itself simplifies the analysis, though wide individual variation still exists." As this statement implies, riders skill level plays a role in accident avoidance. However, one of the goals of the present study is to validate the use of Equation (1), or a modified form of this equation, for analyzing swerves of riders on three-wheeled motorcycles. If the swerves reported in this study can be successfully analyzed with this equation, then the skill level of the riders in this study does not limit the equation from being applied to riders with different skill levels. The varying willingness limits of the riders can be represented by using lower lateral acceleration limits for riders with lower willingness limits.

Motorcycle and Rider Overview

Motorcycle #1 - Testing was conducted on September 6, 2018. The first motorcycle tested was a black 2018 Harley-Davidson Tri Glide (VIN - 1HD1MAD17JB859222) equipped with a Dunlop MT90B16 front tire and two Dunlop P205/65R15 rear tires (Figure 3). The front tire had an inflation pressure of 38 psi and tread depths that ranged from 4/32 to 6/32 of an inch. The right rear tire had an inflation pressure of 40 psi and a tread depth of approximately 9/32 of an inch. The left rear tire had an inflation pressure of 37 psi and a tread depth of approximately 10/32 of an inch. The discrepancy in tire pressures was not resolved prior to testing. The 1750cc engine of this motorcycle had 93 horsepower.

The motorcycle was equipped with a six-speed manual transmission and a hydraulic braking system in which the brakes were operated with controls on the right-side of the motorcycle similar to a two-wheeled motorcycle. The front brakes were operated with a hand lever and the rear brakes with a foot pedal. The front brakes had a dual rotor and a single caliper per rotor, and the rear brakes had a single rotor and single caliper at each wheel. The motorcycle was not equipped with antilock brakes, but the owner's manual reported that there was some degree of integration of the front and rear brakes. Application of the front brake lever would only apply the front brake, but application of the rear brake pedal would apply the rear brake and some front brake.

A set of calibrated PWW-16K-4 portable wheel scales were used to weigh the motorcycles. These wheel scales had a capacity of 10,000 pounds and a resolution of 2 pounds. The weights were displayed on an AX-5 indicator. Motorcycle #1 weighed 1,216 pounds without any instrumentation or a rider. The weight on the front wheel was 370 pounds and the combined weight on the rear wheels was 846 pounds. Thus, approximately 30.5% of the weight was on the front axle and 69.5% was on the rear. This motorcycle has a 66-inch wheelbase and a 45-inch rear track width. Given the front and rear wheel loads, the distance from the front axle to the center of gravity was 45.9 inches.

To gather data for calculating the center of gravity height of this motorcycle, the front end was elevated 6 inches and the motorcycle was reweighed (Figure 4). The elevation of the front wheel resulted in a difference in the pitch orientation of the motorcycle of approximately 5.5 degrees between the two configurations in which it was weighed. In the second configuration, the weight on the front wheel was 358 pounds and the weight on the rear wheels was 854 pounds, yielding a total weight of 1,212 pounds. Thus, there was a 2-pound

FIGURE 3 Motorcycle #1, 2018 Harley-Davidson Tri Glide Ultra.

FIGURE 4 Motorcycle #1 being weighed with the front end elevated.

discrepancy between what the scales read in this instance and when the motorcycle was weighed without the front wheel elevated. Based on these weights, a center of gravity height of 21.4 inches was calculated using the methods in References 19 and 20.

As a comparison, Rose and Neale [13] reported the following equation for estimating the center of gravity height of two-wheeled cruiser or touring motorcycles.

$$h = 0.2777 \times WB \pm 0.0454 \times WB \quad (3)$$

If this equation was applied to the subject three-wheeled motorcycle, it would yield a center of gravity of 18.3 inches ± 3.0 inches. The measured center of gravity height for Motorcycle #1 falls near the upper end of this range.

This center of gravity height can be used with Equation (2) to estimate the lateral acceleration necessary to cause a this three-wheeled motorcycle to begin rolling over, as follows:

$$f_{y,limit} = \frac{T_{rear}}{2h} \cdot \frac{a}{l_w} = \frac{45\,in}{2 \times 21.4\,in} \cdot \frac{45.9\,in}{66\,in}$$

$$f_{y,limit} = 0.73$$

If the riders weight were incorporated into this calculation, the combined center of gravity height would be approximately 23.1 inches and the average lateral acceleration limit would decrease to 0.68. This calculation assumes the rider is fully paired to the motorcycle.

Elevating the front wheel of this motorcycle by 6 inches resulted in an inclination angle of approximately 5.5 degrees. Generally, a higher inclination angle will result in less uncertainty when determining a vehicle's center of gravity height [19, 20]. In an attempt to verify the center of gravity height of this motorcycle and to achieve a higher inclination angle, a second inspection of this motorcycle was conducted on October 8, 2018. This time, an inclination angle of approximately 10.5 degrees was achieved (Figure 5), which resulted in a 26-pound difference between the elevated and non-elevated positions. The wheel weights obtained during this inspection led to a calculated center of gravity height for this motorcycle of 21.1 inches, within 0.3 inches of the first measurement.

Motorcycle #2 - The second motorcycle in this study was a red and tan 2018 Harley-Davidson Tri Glide (VIN - 1HD1MAD16JB859101) equipped with a Dunlop MT90B16 front tire and Dunlop P205/65R15 rear tires (Figure 6). The front tire had an inflation pressure of 42 psi and tread depths that ranged from 4/32 to 5/32 of an inch. The right rear tire had an inflation pressure of 27 psi and a tread depth of approximately 10/32 of an inch. The left rear tire had an inflation pressure of 25 psi and a tread depth of approximately 10/32 of an inch. This motorcycle was also equipped with a 1750cc engine with 93 horsepower. The motorcycle was equipped with a six-speed manual transmission and a hydraulic braking system in which the brakes were operated with the right-side controls, the front brakes with the hand lever and the rear brakes with the foot pedal. The front brakes had a dual rotor and a single caliper per rotor, and the rear brakes had a single rotor and single caliper at each wheel. The motorcycle was not equipped with antilock brakes, but the owner's manual reported that there was some degree of integration of the front and rear brakes. Application of the front brake lever would only apply the front brake, but application of the rear brake pedal would apply the rear brake and some front brake.

This motorcycle weighed 1,214 pounds without any instrumentation or a rider. The weight on the front wheel was 372 pounds and the combined weight on the rear wheels was 842 pounds. Thus, approximately 30.5% of the weight was on the front axle and 69.5% was on the rear. With Rider #1 on this motorcycle, the weight on the front wheel was 432 pounds and the combined weight on the rear wheels was 972 pounds, putting 30.8% of the weight on the front wheel and 69.2% on the rear wheels. The weight distribution of this motorcycle with Rider #2 was nearly identical to that with Rider #1.

Motorcycle #2 was also tested with ballast, which when combined with the instrumentation weighed approximately 246 pounds. Part of the ballast was placed on the passenger's seat and part of it was placed in the rear luggage compartment (Figure 7). This resulted in a total weight of 1,650 pounds, including Rider #2, the instrumentation, and the ballast. The weight on the front wheel was 400 pounds and the combined weight on the rear wheels was 1,250 pounds.

Rider #1 - The first rider was a relatively new rider, but one who had completed the Motorcycle Safety Foundation's (MSF) Basic and Advanced Rider Courses and who, weather permitting, commutes on his motorcycle daily. This rider's everyday motorcycle is a 2017 Honda Rebel 300 with antilock brakes and his commute consists of urban streets and

FIGURE 5 Motorcycle #1 being again weighed with the front end elevated.

FIGURE 6 Motorcycle #2, 2018 Harley-Davidson Tri Glide Ultra

FIGURE 7 Motorcycle #2 with Ballast and Instrumentation

highways. To familiarize himself with the handling of the three-wheeled motorcycles used in this study, this rider rode Motorcycle #2 for about 50 miles on urban streets and highways prior to the testing. During testing, this rider wore a Shoei full-face helmet, a Dainese motorcycle jacket with armor, jeans, motorcycle boots, and gloves. Including this gear, Rider #1 weighed approximately 190 pounds. This rider was aware of the risks inherent in testing of the nature reported in this study and consented to those risks.

Rider #2 - The second rider has 15 years of riding experience on over 50 different motorcycles. He is certified as an MSF instructor, and has been teaching the Basic and Advanced Rider Courses since 2010. His everyday motorcycle was a Triumph Bonneville. Prior to testing, this rider rode Motorcycle #1 for about 50 miles on urban streets and highways to familiarize himself with the handling of the three-wheeled motorcycles used in this this study. This rider had previously ridden three-wheeled motorcycles and had tested a number of two-wheeled motorcycles under heavy braking and swerving. During testing, this rider wore an Arai three-quarter face helmet, an Icon heavy leather jacket with titanium spine plates and Kevlar pads, jeans, boots and gloves. Including gear, Rider #2 weighed approximately 188 pounds. This rider was aware of the risks inherent in testing of the nature reported here and consented to those risks.

Test Facility and Range Setup

The testing reported in this paper was conducted on September 6, 2018 on the large skid pad at the Douglas County Emergency Vehicle Operations Center (EVOC) near Highlands Ranch and Roxborough, Colorado (Latitude: 39.479718, Longitude: -105.020523). This facility is shown in Figure 8. The test surface was level and consisted of dry, relatively new, well-maintained asphalt. The weather was clear and dry and the temperature at the beginning of the testing was approximately 62 degrees, rising to approximately 70 degrees by the time the testing was completed.

Figure 9 shows an aerial image of the setup of the testing area. The layout for the heavy braking test consisted of a start

FIGURE 8 Douglas County Emergency Vehicle Operations Center (EVOC)

FIGURE 9 Diagram Showing Test Setup

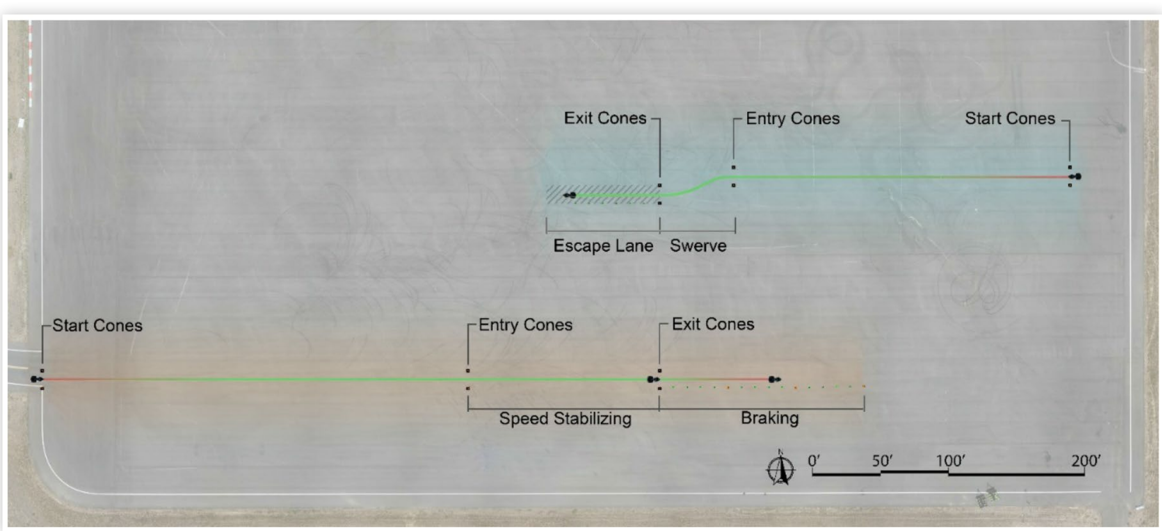

FIGURE 10 Test Area for Heavy Braking

FIGURE 11 Instrumentation Installed on Motorcycle #2

point, designated by two small start cones of the type used in the MSF Basic and Advanced Rider's courses. A set of entry cones was placed 300 feet downstream of the start point. This first 300 feet was intended to be the distance over which the riders would accelerate as quickly and safely as possible from a stop to the target speed for each test. A set of exit cones was placed 100 feet from the entry cones and was intended to be the region where the riders would stabilize their speed. After passing through the exit cones, the riders would apply the brakes of the motorcycle as quickly and safely as possible and come to a complete stop. The area designated for heavy braking is shown in Figure 10.

After remaining in a stopped position for several seconds, the rider would proceed to the beginning of the swerve test section. The layout for the swerve tests consisted of two start cones where the rider would come to a complete stop prior to beginning the test. After several seconds, the rider would accelerate to a set of entry cones placed 250' away. Over this distance, the rider would achieve and stabilize the swerve maneuver entry speed. After passing through the swerve maneuver entry cones, the riders would swerve to the left, into a 12-foot-wide marked escape lane that is offset 12 feet from the swerve entry cones. This channel of cones set at 12-foot-wide essentially mimics a real-world scenario, where a rider, presented with a hazard in their lane of travel, could swerve to an open lane to their left.

Instrumentation

For each test, the path, speed, and lean angle of the rear of the motorcycle were continuously recorded at 20 Hz using a Racelogic VBOX (Figure 11). The VBOX system utilized two GPS antenna magnetically attached near the outer extents of a metal crossbar. The crossbar was attached to the rear of the motorcycle. The authors have utilized a similar setup in two prior studies with motorcycles [21, 22]. A tri-axial accelerometer was also paired with the VBOX and attached near the center of the crossbar. The VBOX data logger was carried in the lower rear luggage compartment of the motorcycle. During analysis, the speed and acceleration data were filtered with a low pass digital Butterworth filter to reduce noise. This

FIGURE 12 The sUAVs used for video footage of the testing.

filter was a two-channel filter and was run once forward and once backward to prevent phase displacements. The 3dB limit frequency was set to 3.33 Hz. Testing was also captured with multiple ground level video cameras and cameras attached to multiple small unmanned aerial vehicles (sUAV). These sUAVs, which included a Mavic Pro, a Phantom 3 Pro, and a Phantom 4 Pro+, are depicted in Figure 12. All cameras recorded at a rate of 30 fps.

Test Matrix

A total of 25 tests were performed in which the operator attempted to maximize the deceleration of the motorcycle. Since there was little potential for the motorcycles to capsize during heavy braking, the riders often braked hard enough to lock the wheels and deposit tire marks. Table 1 shows the test matrix for these 25 tests. This table lists the rider, the motorcycle, and the brakes employed for each test. As this table shows, 9 tests were performed with application of both the front and rear brakes, 7 tests were run with the front brake only, and 9 tests were run with application of the rear brake pedal only. A total of 25 swerve tests were also performed. These tests employed the same rider and motorcycle combinations as those listed in Table 1.

TABLE 1 Matrix for Maximal Deceleration Tests

Test #	Rider	M/C	Brakes Lever or Pedal Employed
1	1	1	front and rear
2	1	1	front only
3	1	1	rear only
4	1	1	front and rear
5	1	1	front only
6	1	1	rear only
7	1	1	front and rear
8	1	1	front only
9	1	1	rear only
10	1	1	front and rear
11	1	1	front only
12	1	1	rear only
13	1	1	front and rear
14	1	1	front only
15	1	1	rear only
16	1	1	front and rear
17	1	1	front only
18	1	1	rear only
19	2	2	front and rear
20	2	2	front only
21	2	2	rear only
22	2	2	front and rear
23	2	2	rear only
24	2	2 + ballast	front and rear
25	2	2 + ballast	rear only

Results and Analysis

Braking

The test results for the maximal braking tests are presented graphically in Figures A1 through A50 in Appendix A. For each test, both a speed graph and an acceleration graph are presented. Each graph has time, in seconds, plotted on the horizontal axis and either speed, in mph, or acceleration, in g, plotted on the vertical axis. Although not the focus of this study, the data in these graphs shows that the riders utilized average accelerations in the range of 0.3 to 0.4 g in accelerating up to the test speeds.

Table 2 summarizes the results of the heavy braking tests that utilized both the front and rear brakes. Table 3 summarizes the results of the heavy braking tests that used the front brake only. Table 4 summarizes the results for the heavy braking tests that used the rear brake pedal only. The initial speed reported for each test is the speed that was reported by the VBOX at the instant the heavy braking pulse began to build up. The average decelerations during the heavy braking were calculated by averaging the acceleration readings over the entire heavy braking pulse, including the ramp up and ramp down of the deceleration [23]. The peak deceleration was calculated by averaging the readings over the plateauing region of the deceleration pulses.

TABLE 2 Results for Maximal Deceleration Tests Utilizing Both **Front and Rear Brakes**

Test #	Initial Speed (mph)	Rider & M/C	Average Deceleration (g)	Peak Deceleration (g)
1	35.6	1, 1	0.74	0.92
4	34.5	1, 1	0.86	0.94
7	33.2	1, 1	0.85	0.92
10	43.0	1, 1	0.81	0.85
13	46.1	1, 1	0.85	0.91
16	46.8	1, 1	0.84	0.91
19	28.9	2, 2	0.86	0.93
22	45.2	2, 2	0.91	0.95
24	50.1	2, 2+ballast	0.78	0.88
Ave			0.83	0.91

TABLE 3 - Results for Maximal Deceleration Tests Utilizing **Front Brake Only**

Test #	Initial Speed (mph)	Rider & M/C	Average Deceleration (g)	Peak Deceleration (g)
2	33.2	1, 1	0.37	0.39
5	31.3	1, 1	0.37	0.39
8	28.1	1, 1	0.40	0.41
11	45.7	1, 1	0.39	0.39
14	48.4	1, 1	0.36	0.37
17	48.3	1, 1	0.38	0.38
20	29.8	2, 2	0.42	0.43
Ave			0.39	0.39

TABLE 4 - Results for Maximal Deceleration Tests Utilizing **Rear Brake Pedal Only**

Test #	Initial Speed (mph)	Rider & M/C	Average Deceleration (g)	Peak Deceleration (g)
3	33.7	1, 1	0.70	0.83
6	33.6	1, 1	0.74	0.86
9	33.3	1, 1	0.79	0.89
12	43.7	1, 1	0.78	0.83
15	50.6	1, 1	0.70	0.75
18	48.0	1, 1	0.70	0.74
21	29.1	2, 2	0.84	0.93
23	47.7	2, 2	0.80	0.84
25	52.5	2, 2+ballast	0.73	0.77
Ave			0.75	0.83

Swerving

The test results for the swerve tests are presented graphically in Figures B1 through B75 in Appendix B. For each test, a speed graph, a lateral acceleration graph, and a heading graph are presented. Each graph has time, in seconds, plotted on the horizontal axis and either speed, in mph, acceleration, in g, or heading, in degrees, plotted on the vertical axis.

TABLE 5 Results for Swerve Tests

Test #	Average Speed (mph)	Ave Lat Acc (g)	Lateral Dist (ft)	Actual Long Dist (ft)	Calc Long Dist (ft)	Error (%)
1	21.7	0.34	8.4	64.2	56.2	-13.0
2	24.2	0.38	9.2	64.5	62.0	-4.4
3	22.0	0.43	9.8	64.6	54.2	-15.8
4	18.2	0.39	9.8	47.5	48.8	-0.6
5	25.1	0.37	10.1	76.2	68.8	-10.9
6	22.7	0.38	10.8	65.0	64.7	-3.6
7	29.7	0.40	10.8	90.4	80.3	-11.6
8	30.9	0.41	9.3	89.9	79.6	-15.3
9	30.1	0.36	10.0	98.2	83.9	-16.4
10	33.8	0.33	9.7	105.9	94.7	-10.4
11	30.8	0.40	9.6	78.4	79.4	-0.4
12	32.4	0.46	10.2	77.6	78.5	1.8
13	34.9	0.44	10.4	99.2	87.6	-11.5
14	36.2	0.38	9.9	97.6	95.5	-2.0
15	36.9	0.34	10.5	102.2	106.0	3.9
16	35.1	0.36	10.3	107.2	95.9	-9.3
17	32.0	0.41	9.7	81.3	81.6	-0.9
18	33.6	0.33	10.3	107.5	99.2	-9.6
19	19.9	0.42	8.8	49.7	47.0	-5.1
20	23.5	0.35	7.9	64.5	57.5	-10.4
21	20.9	0.46	8.8	47.7	48.4	-0.8
22	28.7	0.41	8.5	73.0	67.3	-7.3
23	33.1	0.45	8.2	79.5	73.7	-8.0
24	29.1	0.36	9.6	84.6	76.2	-8.1
25	29.4	0.41	8.1	81.3	66.9	-16.8
Average						-7.5
Max						-16.8

Table 5 summarizes the results of the swerve tests. The average speed reported for each test is the average of the individual speed readings over the duration of the swerve. The duration and extents of the swerves were identified using the lateral acceleration and heading angles measured with the VBOX and the accelerometer. The average lateral acceleration during each swerve was calculated by averaging the acceleration readings over the entire swerve. The lateral and longitudinal distances for each swerve were determined from the positional data reported by the VBOX. The calculated longitudinal distances reported in Table 5 were calculated with Equation (1). The percent error was calculated by taking the difference between the calculated longitudinal distance and the actual longitudinal distance and dividing by the actual longitudinal distance.

Table 6 lists additional results from the swerve tests. The average lateral acceleration during each portion of the swerve was calculated by averaging the acceleration readings over the swerve segments. The left steer portion of the swerve was assumed to begin when the lateral acceleration began ramping up quickly from zero and to end when it returned to zero. The right steer portion of the swerve was assumed to begin when the lateral acceleration began ramping up to from zero to its peak negative value and to end when it returned to zero.

TABLE 6 Additional Results for Swerve Tests

Test #	Left Steer Ave Lat Acc (g)	Left Steer Peak Lat Acc (g)	Ratio (Peak to Ave)	Right Steer Ave Lat Acc (g)	Right Steer Peak Lat Acc (g)	Ratio (Peak to Ave)
1	0.38	0.69	1.82	0.28	0.58	2.07
2	0.43	0.71	1.65	0.32	0.53	1.66
3	0.56	1.13	2.02	0.30	0.55	1.83
4	0.48	1.14	2.38	0.31	0.79	2.55
5	0.42	0.76	1.81	0.31	0.58	1.87
6	0.45	0.78	1.73	0.32	0.66	2.06
7	0.47	0.88	1.87	0.32	0.59	1.84
8	0.42	0.85	2.02	0.39	0.65	1.67
9	0.32	0.74	2.31	0.39	0.81	2.08
10	0.29	0.69	2.38	0.37	0.62	1.68
11	0.41	0.75	1.83	0.40	0.64	1.60
12	0.48	0.71	1.48	0.44	0.71	1.61
13	0.39	0.72	1.85	0.49	0.77	1.57
14	0.37	0.78	2.11	0.38	0.61	1.61
15	0.41	0.89	2.17	0.27	0.55	2.04
16	0.36	0.69	1.92	0.36	0.61	1.69
17	0.37	0.85	2.30	0.45	0.72	1.60
18	0.36	0.60	1.67	0.31	0.52	1.68
19	0.44	0.92	2.09	0.40	0.69	1.73
20	0.34	0.92	2.71	0.37	0.55	1.49
21	0.49	1.00	2.04	0.43	0.70	1.63
22	0.45	0.83	1.84	0.37	0.60	1.62
23	0.43	0.77	1.79	0.47	0.75	1.60
24	0.37	0.53	1.43	0.35	0.51	1.46
25	0.42	0.70	1.67	0.41	0.59	1.44
Average			1.96			1.75
Min	0.29	0.60	1.43	0.27	0.51	1.44
Max	0.56	1.14	2.38	0.49	0.81	2.55

Discussion

Braking

The average decelerations for the tests that utilized both the front and rear brakes varied between 0.74 and 0.91 g. This range is situated in the upper half of the corresponding range for two-wheeled motorcycles (0.54 to 0.96 g). This is consistent with the fact that two-wheeled motorcycles require more skill for braking since there is more of a risk of capsizing if the rider locks up a wheel, particularly the front. For the three-wheeled motorcycles, less skill is required since the risk of capsizing is minimal, and the rider can lock up the wheels.

The average decelerations for the tests that utilized the front brake only varied between 0.36 and 0.42 g. This range falls within the range that is typical for rear brake only braking on two-wheeled motorcycles (0.31 to 0.52 g). The average decelerations for the tests that utilized the rear brake pedal only varied between 0.70 and 0.84 g. This range falls within the upper half of the range that is typical for front brake only braking on two-wheeled motorcycles (0.52 to 0.80 g). Rider #2's tests with ballast exhibited lower decelerations than his other runs. However, the decelerations were still within the ranges of values typical for two-wheeled motorcycles.

The braking system on the motorcycles tested in this study is partially integrated in that application of the rear brake also applies some pressure to the front brake even if the operator does not apply the front brake lever. The logic behind this integration scheme seems to be a carry-over from the braking dynamics of two-wheeled motorcycles where a majority of the braking capability comes from the front brake. Based on the decelerations observed in this study, operators of three-wheeled motorcycles like the ones tested in this study could benefit from the logic of the integration being reversed, such that application of the front brake level applies pressure to both the front and rear brakes.

The Motorcycle Safety Foundation offers a dedicated course for riders of three-wheeled motorcycles. Riders taking this course, particularly those accustomed to operating two-wheeled motorcycles, could also benefit from being informed of this difference in the braking dynamics between two-wheeled motorcycles and three-wheeled motorcycles that have two wheels in the back.

This study was limited to testing of three-wheeled motorcycles with two wheels in the rear. Three-wheeled motorcycle models with two wheels in the front seem likely to have a different weight distribution than the ones tested here, and the braking dynamics may be more consistent with what is usually reported for two-wheeled motorcycles. Testing with one of these models could determine if this is the case.

Swerving

The average lateral accelerations for the swerves in this study varied between 0.33 and 0.46 g. The range of average lateral accelerations for the leftward steering portion of the maneuvers was 0.29 to 0.56 g. The range of average lateral accelerations for the rightward steering portion of the maneuvers was between 0.27 to 0.49 g. All of these lateral accelerations fell below the calculated lateral acceleration limit. The range of peak lateral accelerations for the leftward steering portion of the maneuvers was 0.60 to 1.14 g. The range of peak lateral accelerations for the rightward steering portion of the maneuvers was between 0.53 to 0.81 g. The ratio of the peak to the average acceleration varied between 1.43 and 2.38. The total duration of the swerves varied between 1.55 to 2.20 seconds.

Equation (1) tended to underestimate the longitudinal distance needed to complete a swerve of a specified lateral distance. The average error was -7.5% and the maximum error was -16.8%. Analysis was conducted to determine what coefficient for Equation (1) would minimize the error in the calculated longitudinal distance. A coefficient of 0.791 resulted in an average error of 0% and a maximum error of +12.2%. Thus, for the swerves documented in this study, the following equation can be used to estimate the longitudinal distance for a swerve.

$$d_{swerve} = 0.791 \cdot S\sqrt{\frac{L}{f_y}} \tag{4}$$

Conclusions

1. The average decelerations for the tests that utilized both the front and rear brakes varied between 0.74 and 0.91 g.
2. The average decelerations for the tests that utilized the front brake only varied between 0.36 and 0.42 g.
3. The average decelerations for the tests that utilized the rear brake pedal only varied between 0.70 and 0.84 g.
4. The average lateral accelerations for the swerves in this study varied between 0.33 and 0.46 g.
5. Equation (1) tended to underestimate the longitudinal distance needed to make a swerve of a specified lateral distance. The average error was -7.5%, and the range of error across the tests was +3.9% to -16.8%.
6. If the coefficient in Equation (1) is revised to 0.791, then the average error goes to zero and the range of error goes to +12.2% to -10.1%.

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Appendix A - Maximal Deceleration Tests

FIGURE A1 Speed, Braking Test #1, Front and Rear Braking Combined

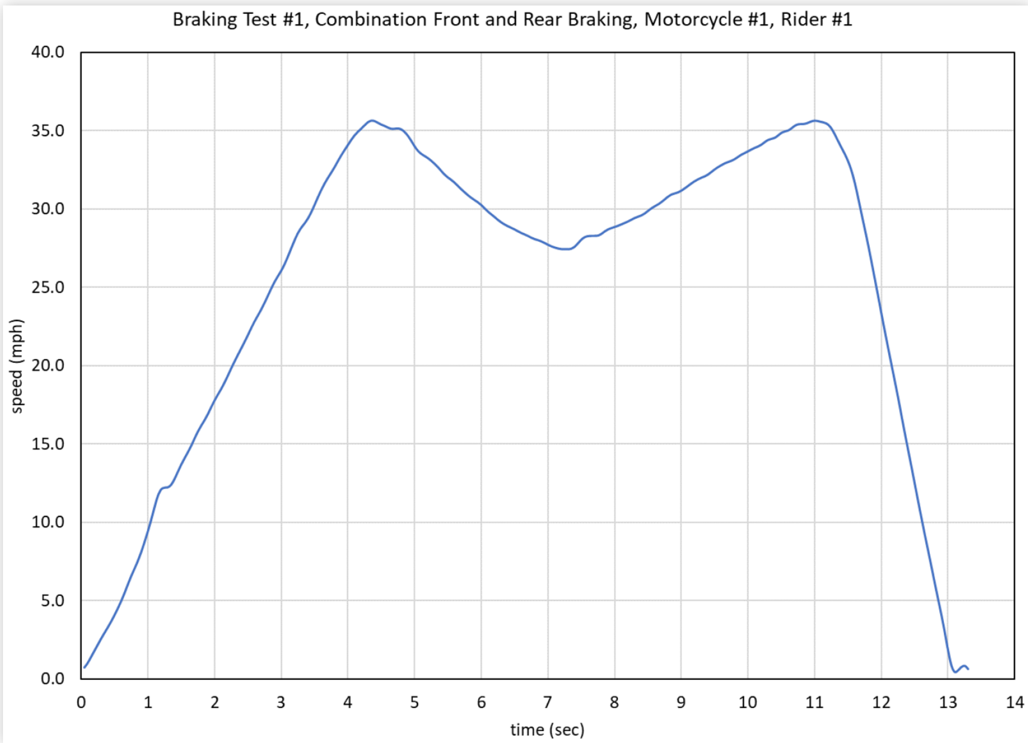


FIGURE A2 Acceleration, Braking Test #1, Front and Rear Braking Combined

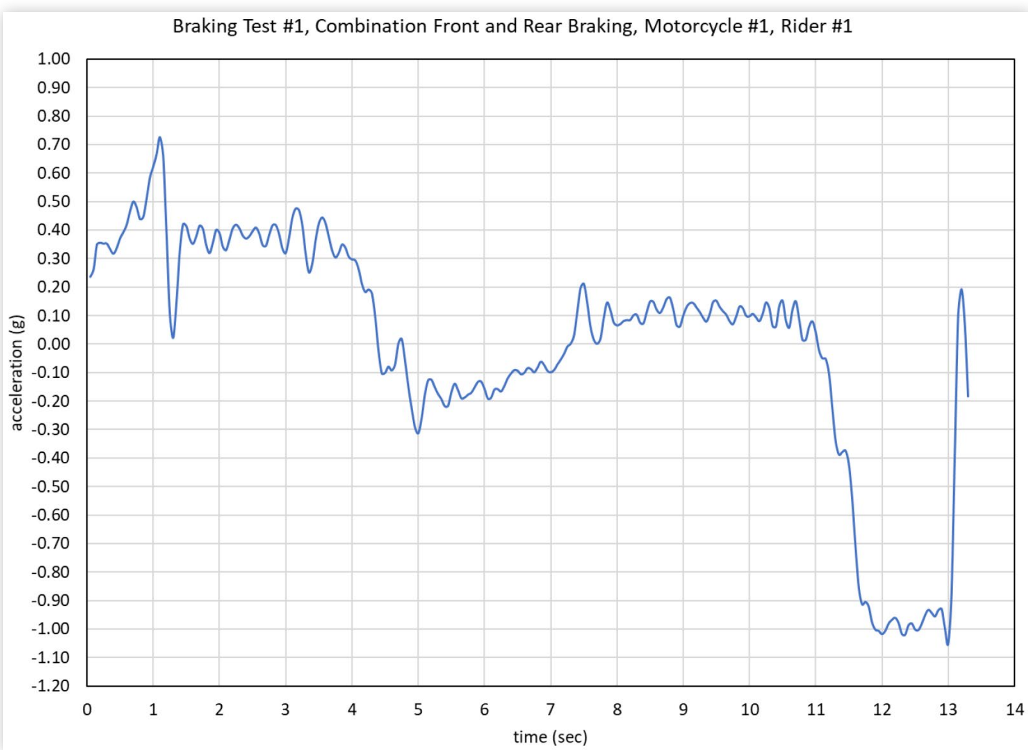


FIGURE A3 Speed, Braking Test #2, Front Braking Only

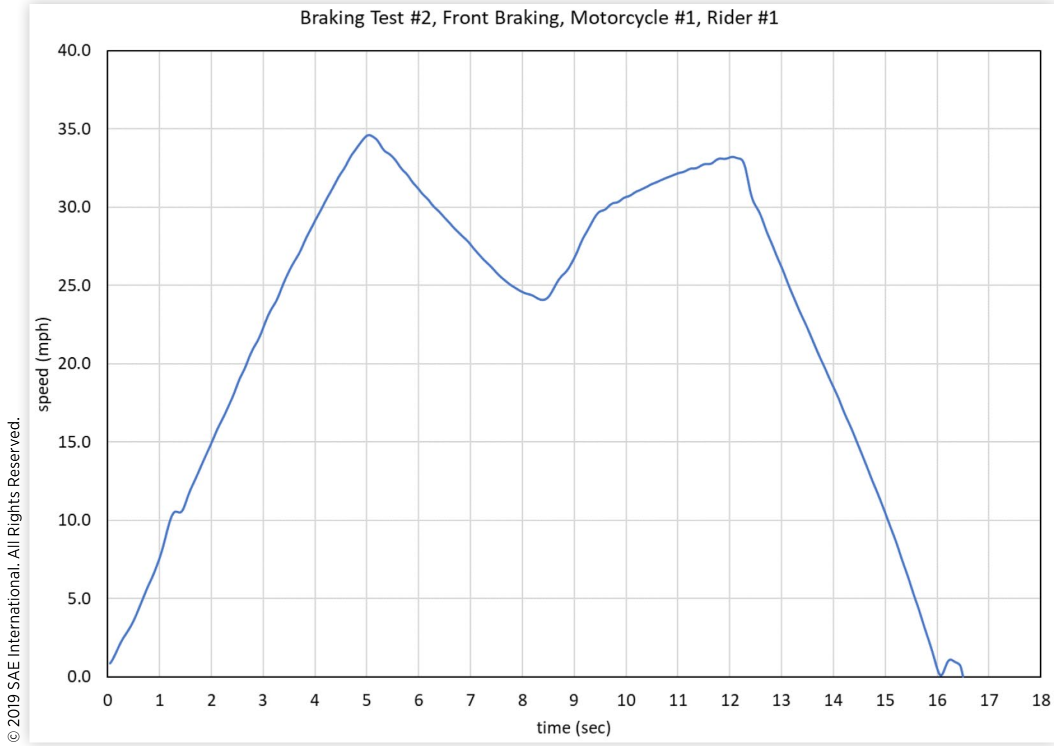


FIGURE A4 Acceleration, Braking Test #2, Front Braking Only

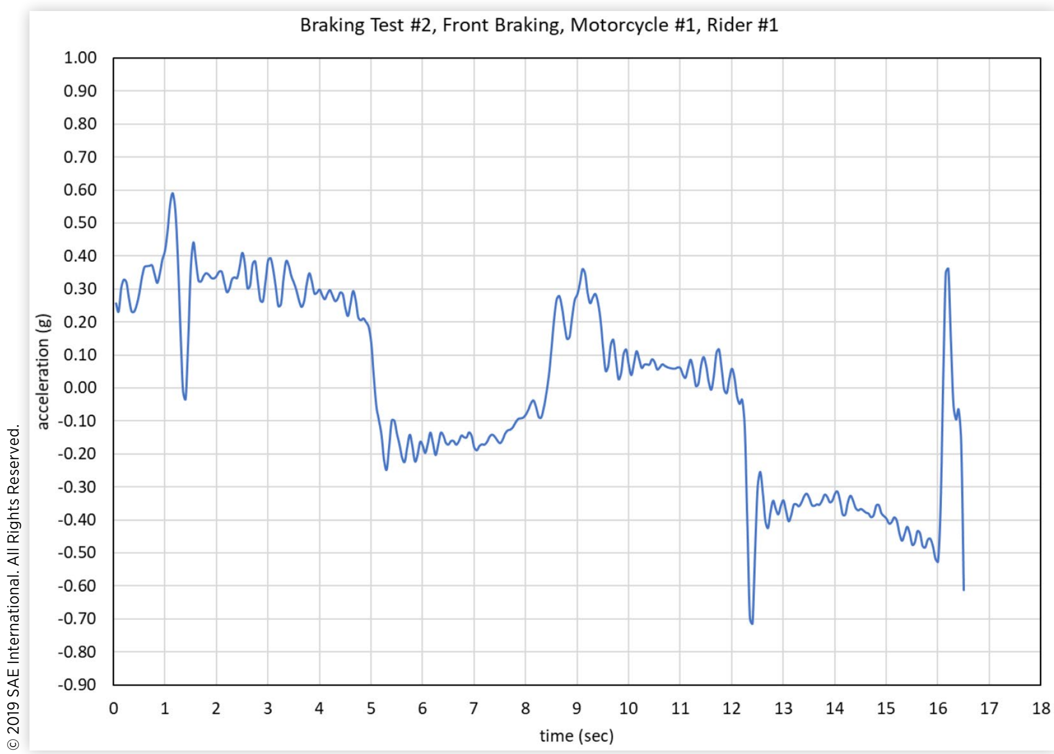


FIGURE A5 Speed, Braking Test #3, Rear Brake Pedal Only

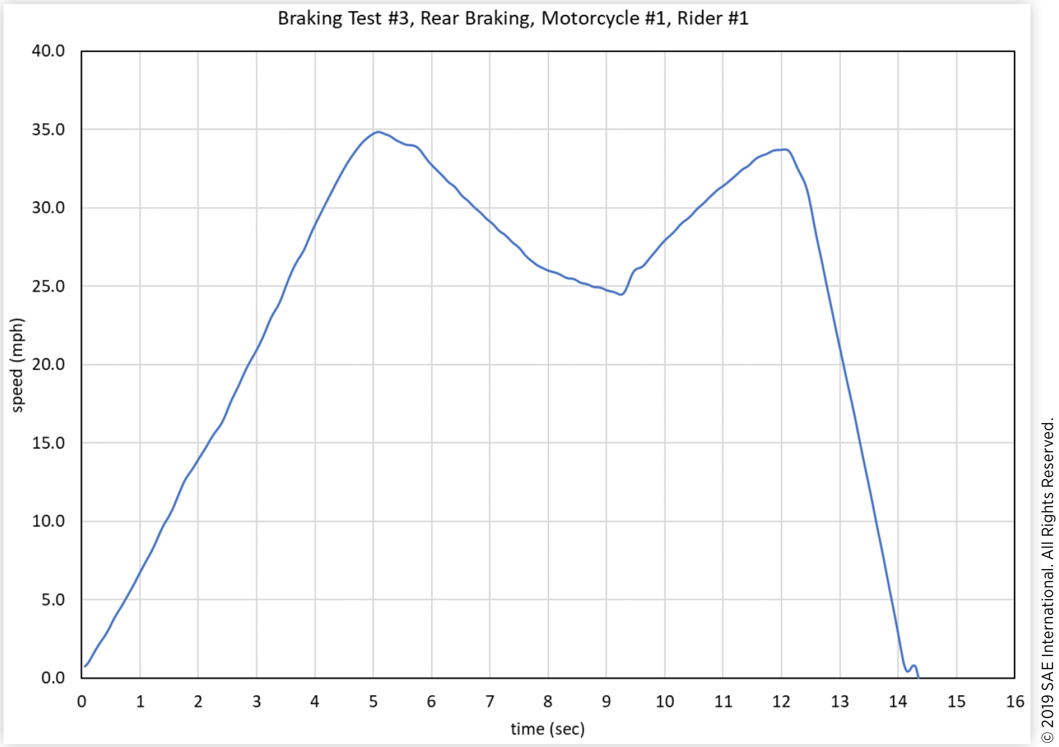


FIGURE A6 Acceleration, Braking Test #3, Rear Brake Pedal Only

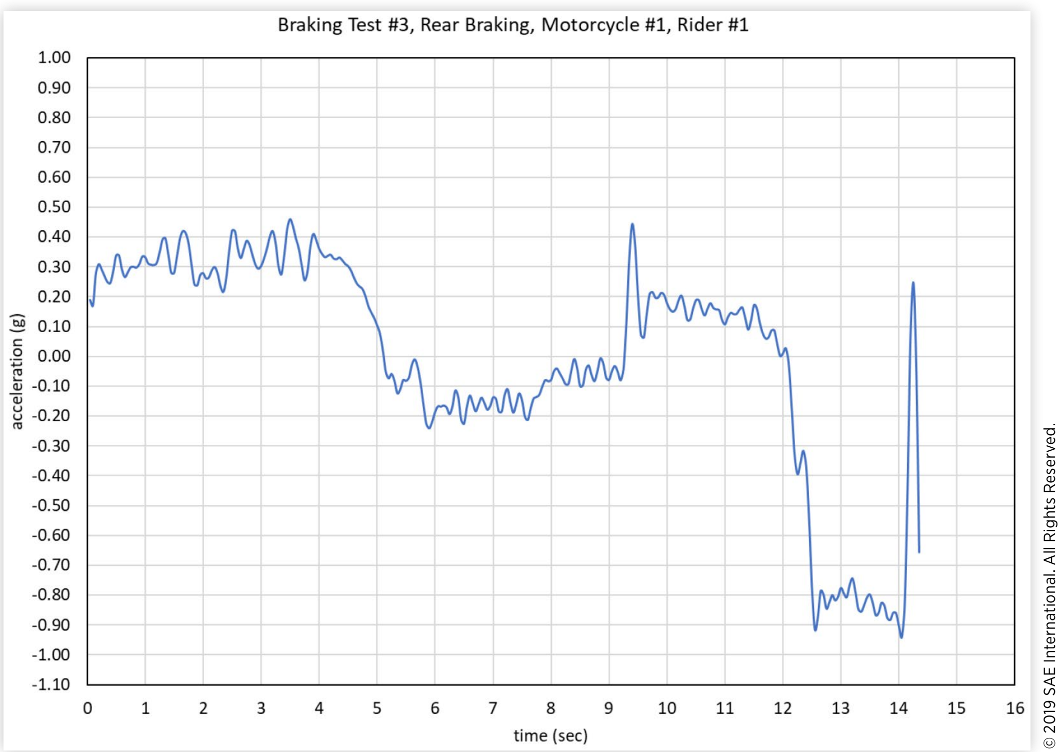


FIGURE A7 Speed, Braking Test #4, Front and Rear Braking Combined

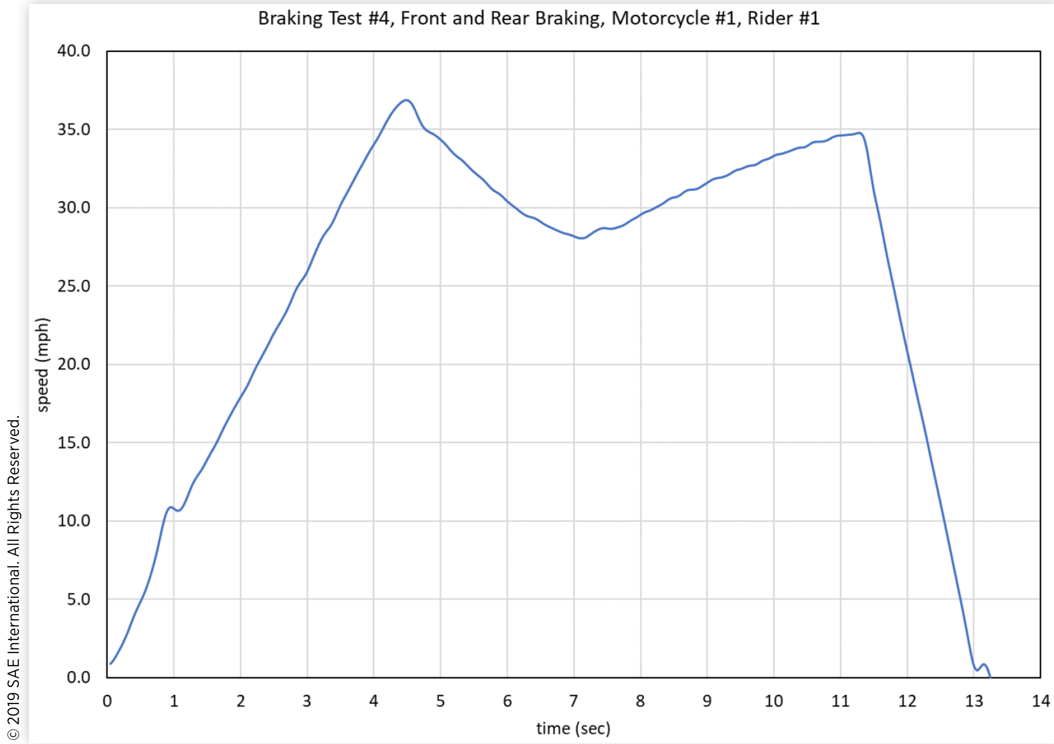


FIGURE A8 Acceleration, Braking Test #4, Front and Rear Braking Combined

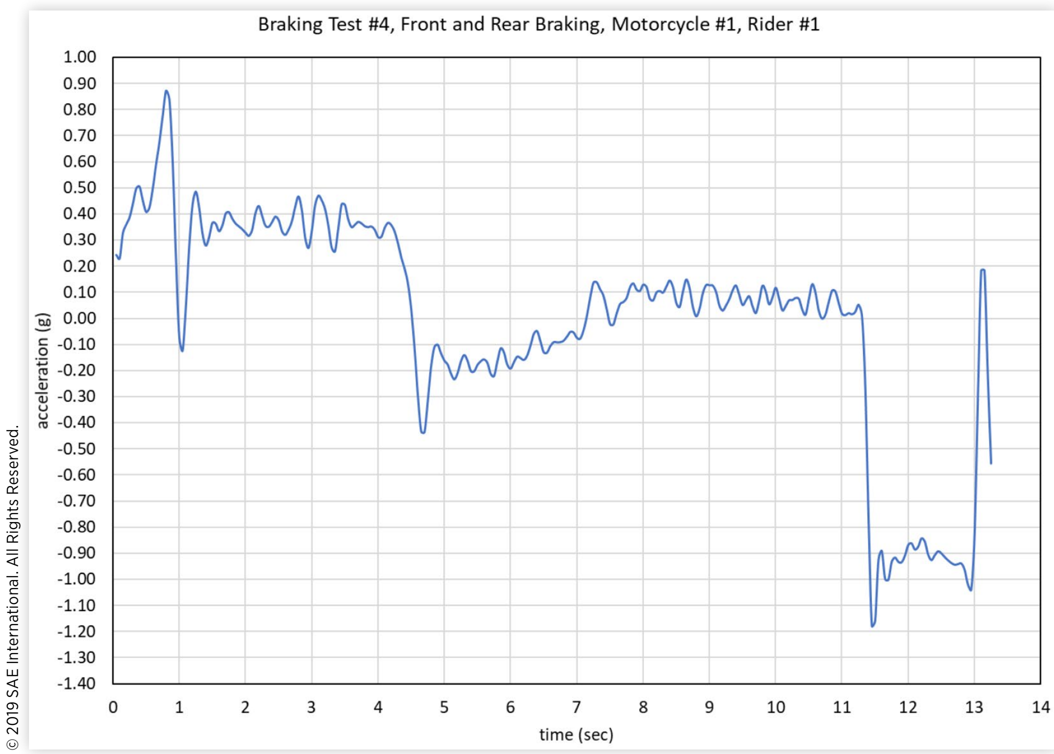


FIGURE A9 Speed, Braking Test #5, Front Braking Only

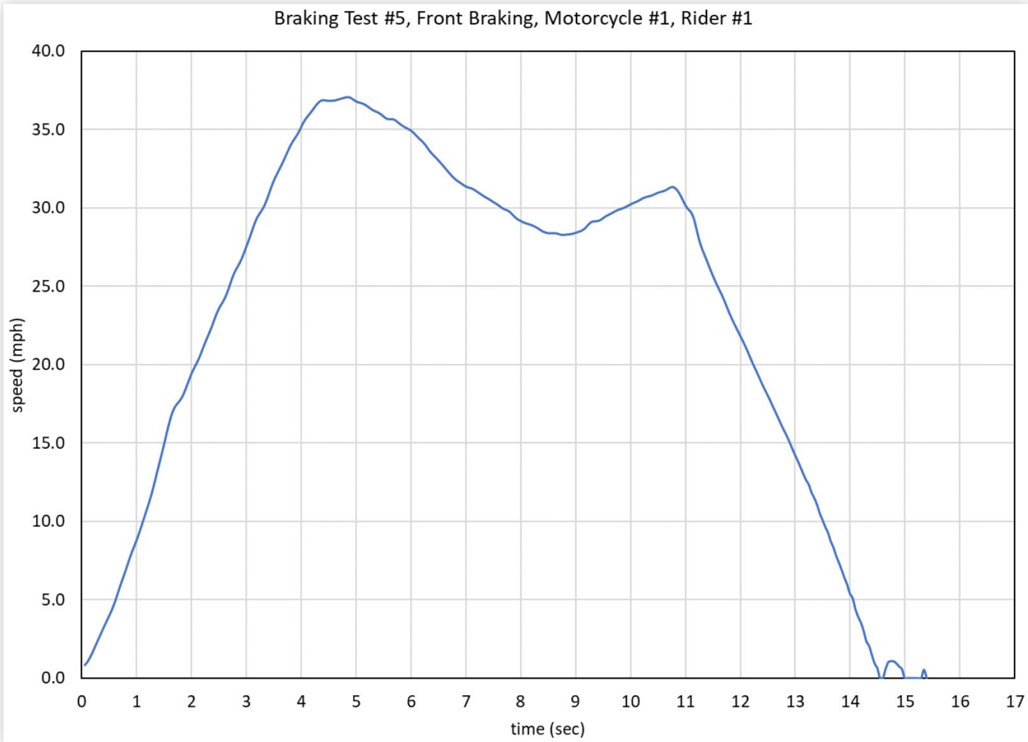


FIGURE A10 Acceleration, Braking Test #5, Front Braking Only

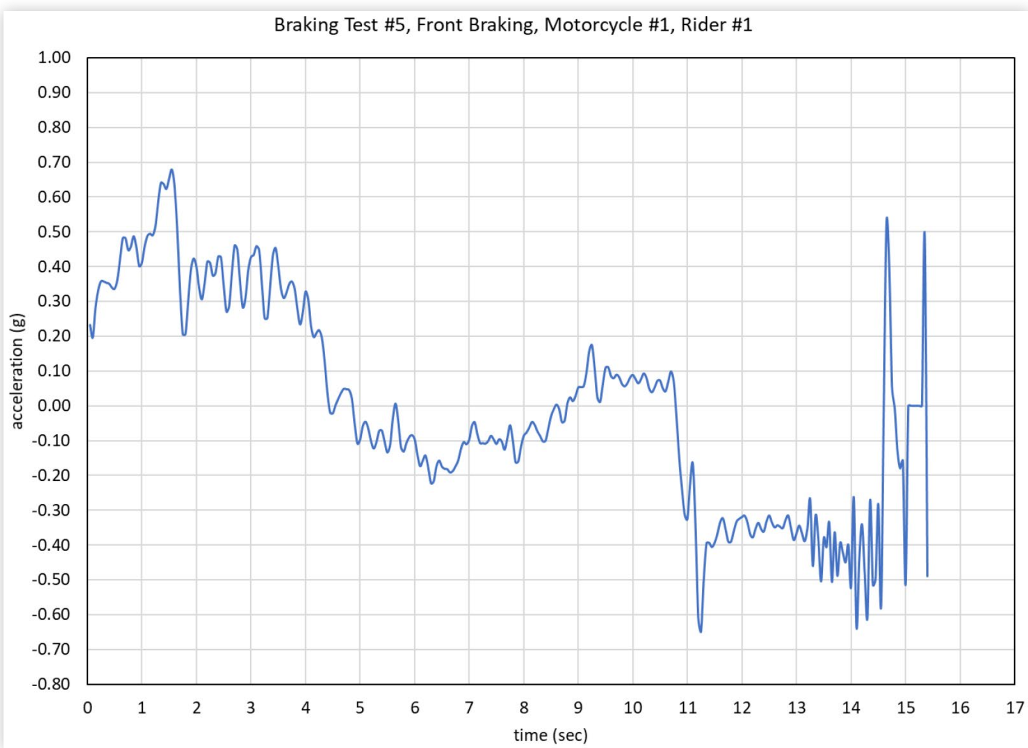


FIGURE A11 Speed, Braking Test #6, Rear Brake Pedal Only

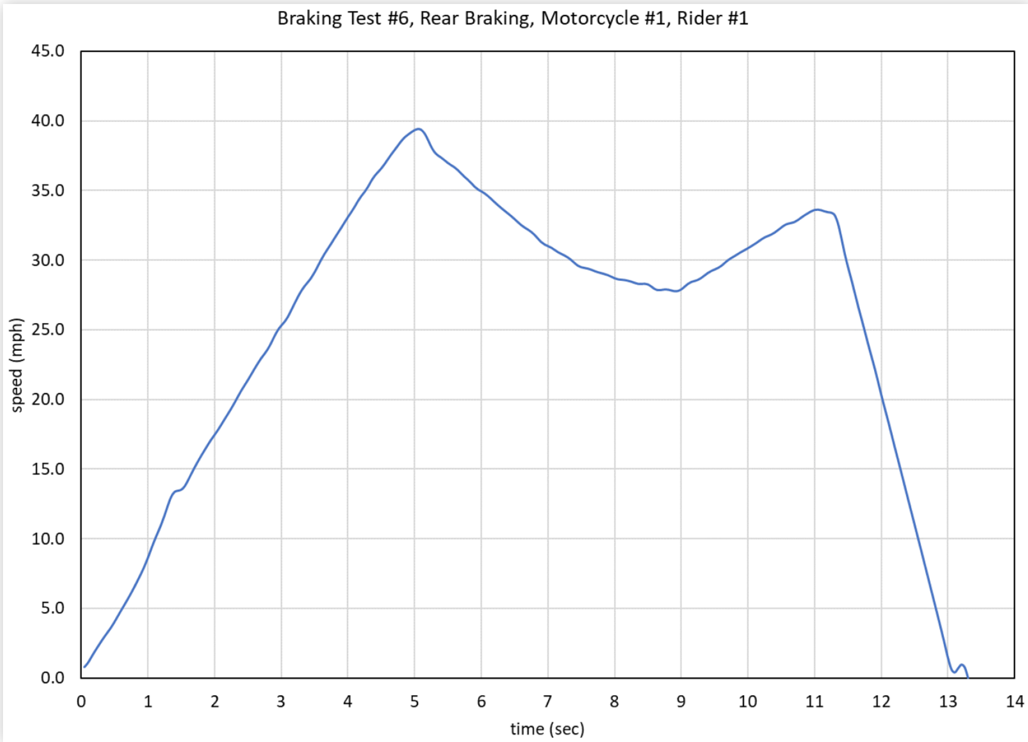


FIGURE A12 Acceleration, Braking Test #6, Rear Brake Pedal Only

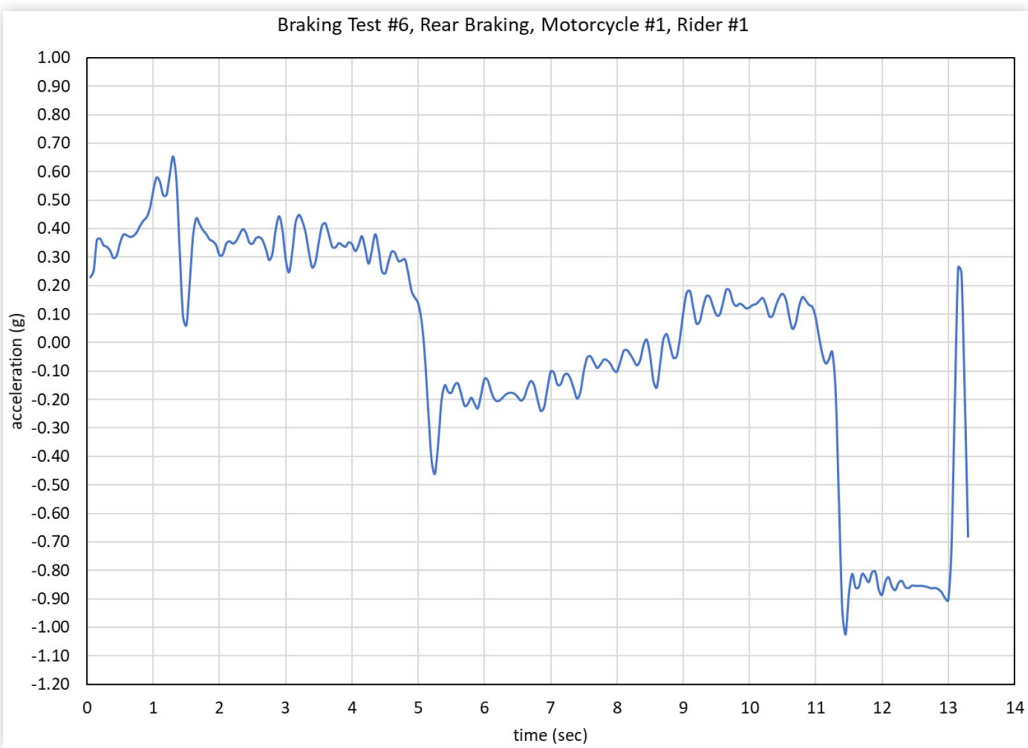


FIGURE A13 Speed, Braking Test #7, Front and Rear Braking Combined

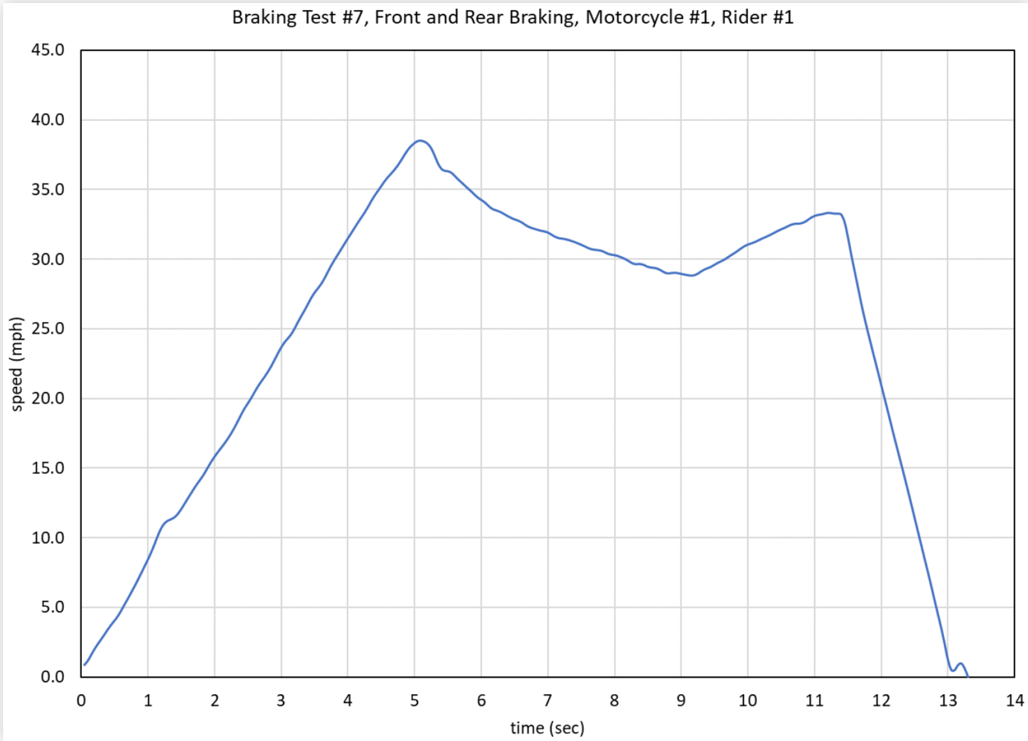


FIGURE A14 Acceleration, Braking Test #7, Front and Rear Braking Combined

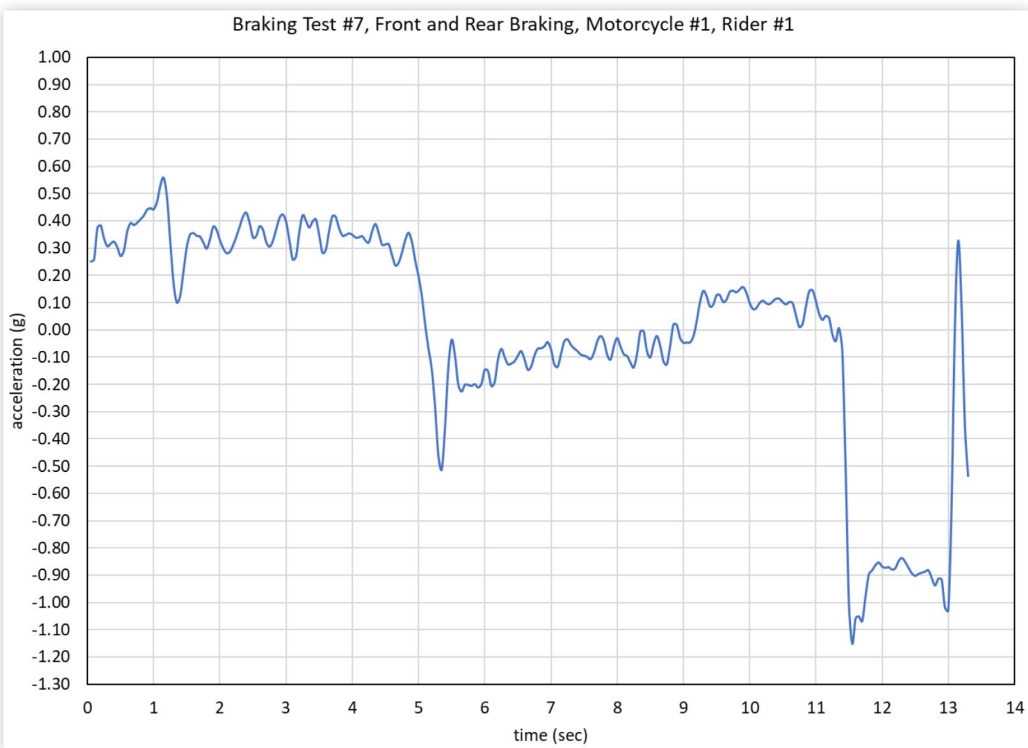


FIGURE A15 Speed, Braking Test #8, Front Braking Only

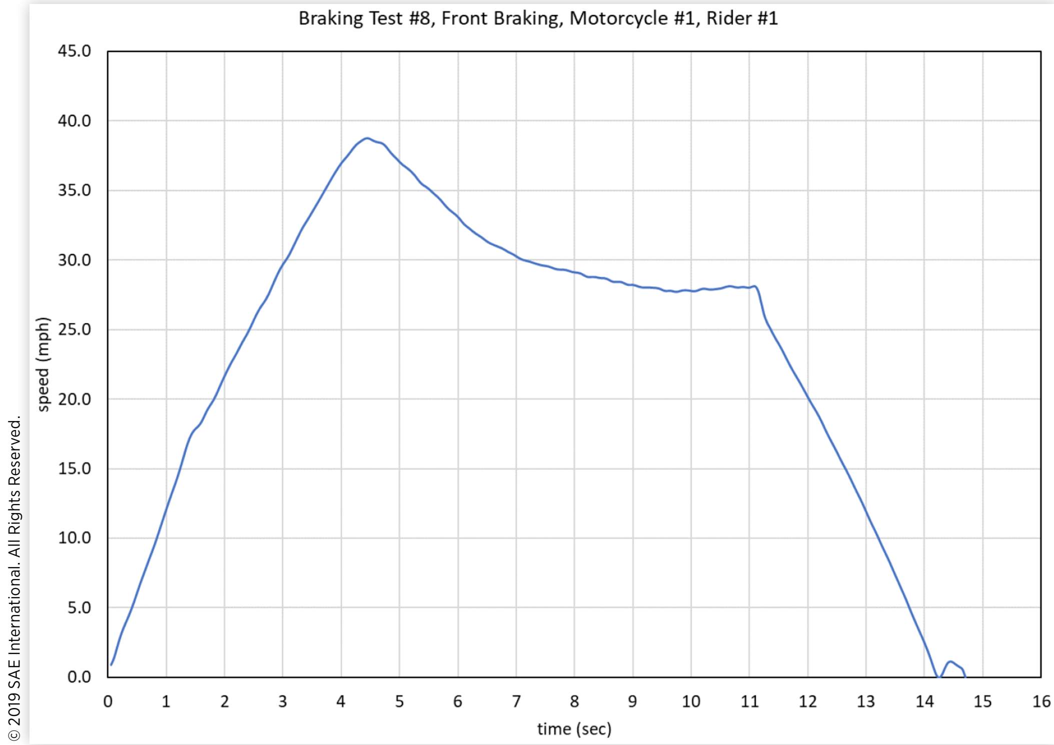


FIGURE A16 Acceleration, Braking Test #8, Front Braking Only

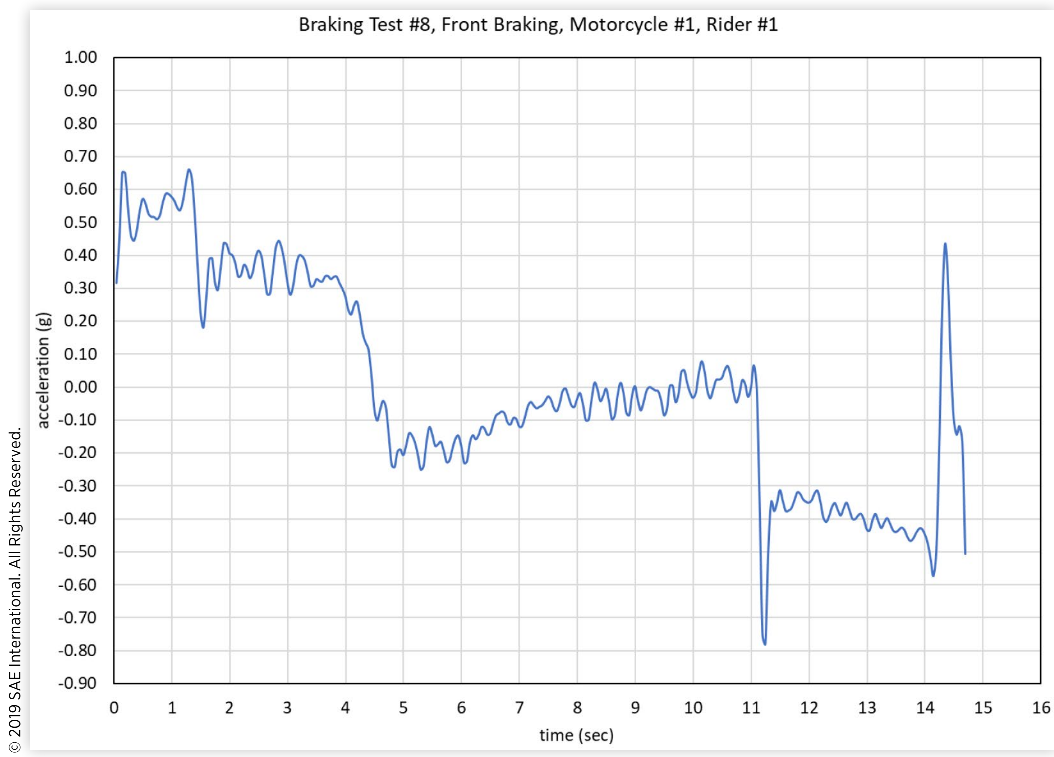


FIGURE A17 Speed, Braking Test #9, Rear Brake Pedal Only

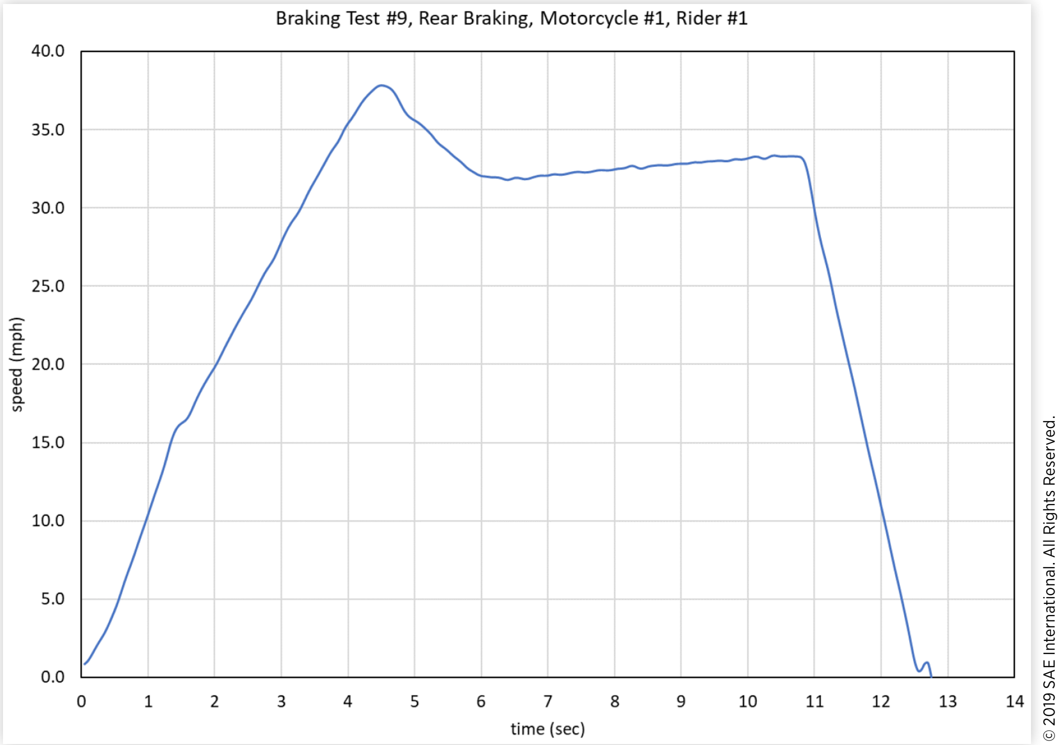


FIGURE A18 Acceleration, Braking Test #9, Rear Brake Pedal Only

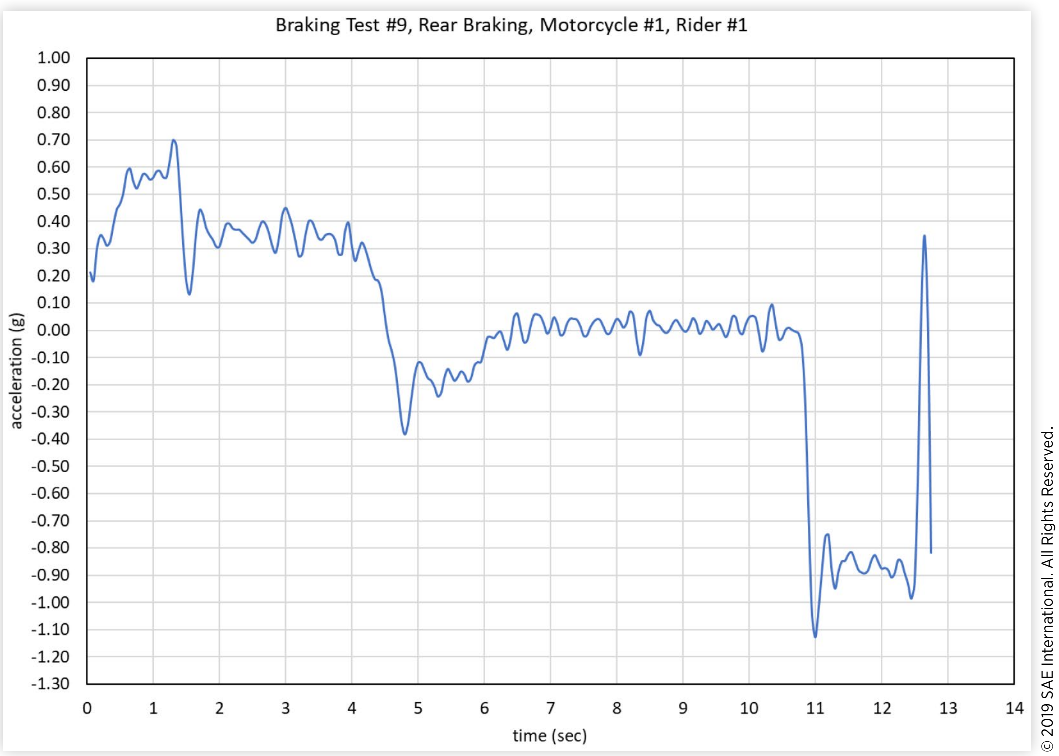


FIGURE A19 Speed, Braking Test #10, Front and Rear Braking Combined

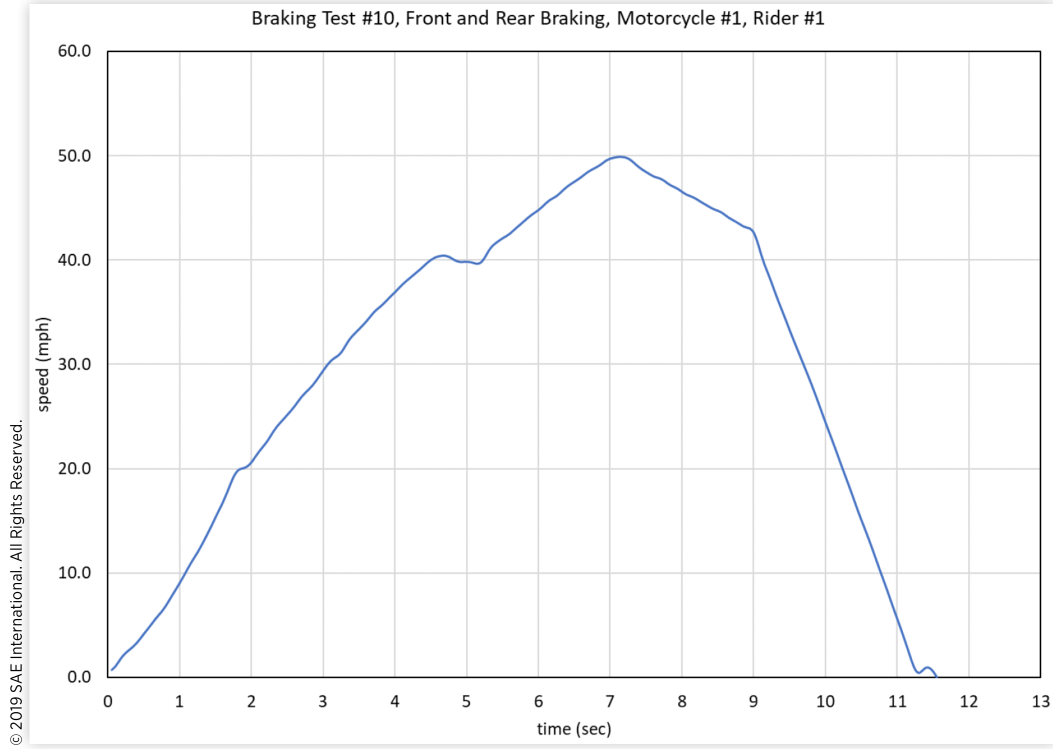


FIGURE A20 Acceleration, Braking Test #10, Front and Rear Braking Combined

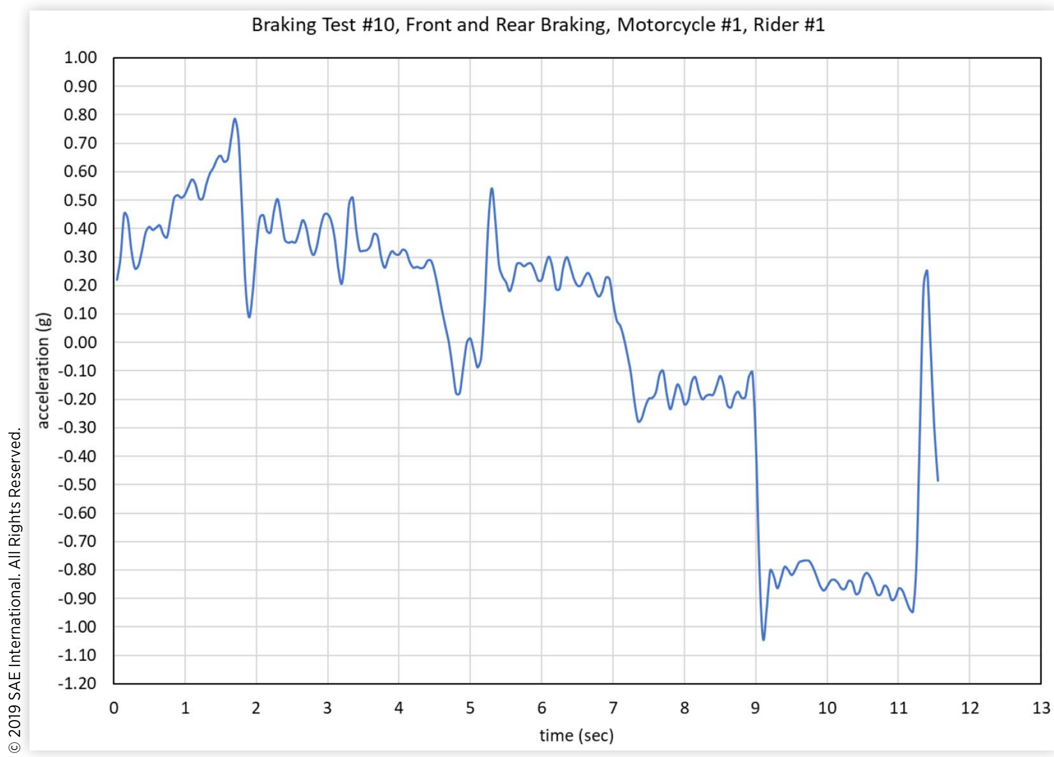


FIGURE A21 Speed, Braking Test #11, Front Braking Only

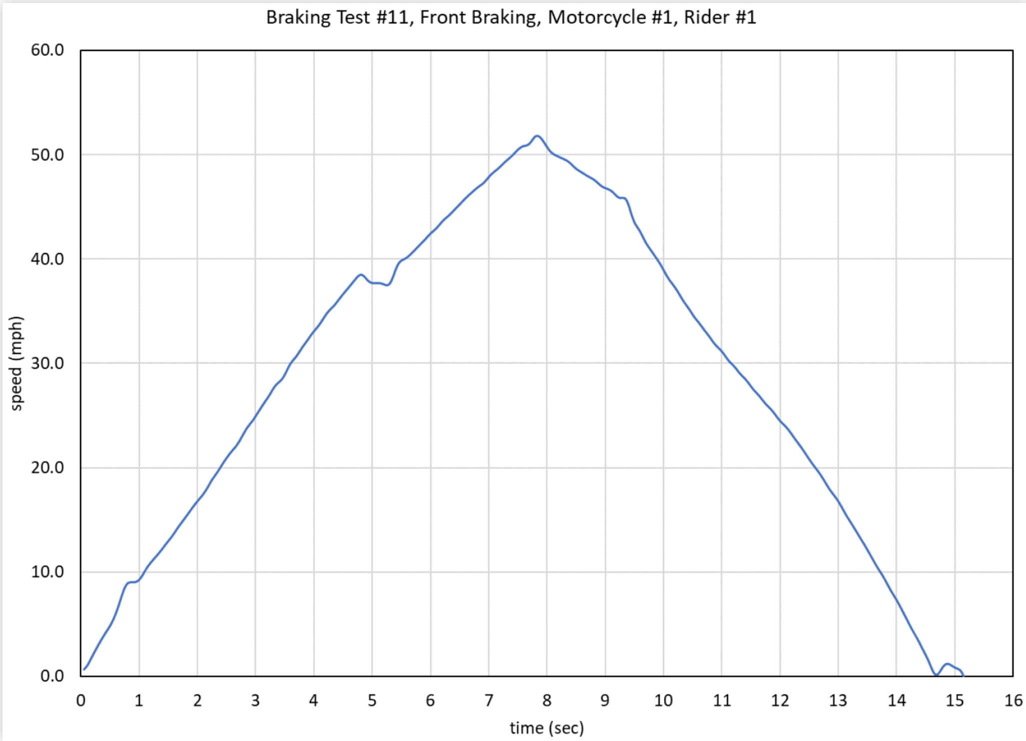


FIGURE A22 Acceleration, Braking Test #11, Front Braking Only

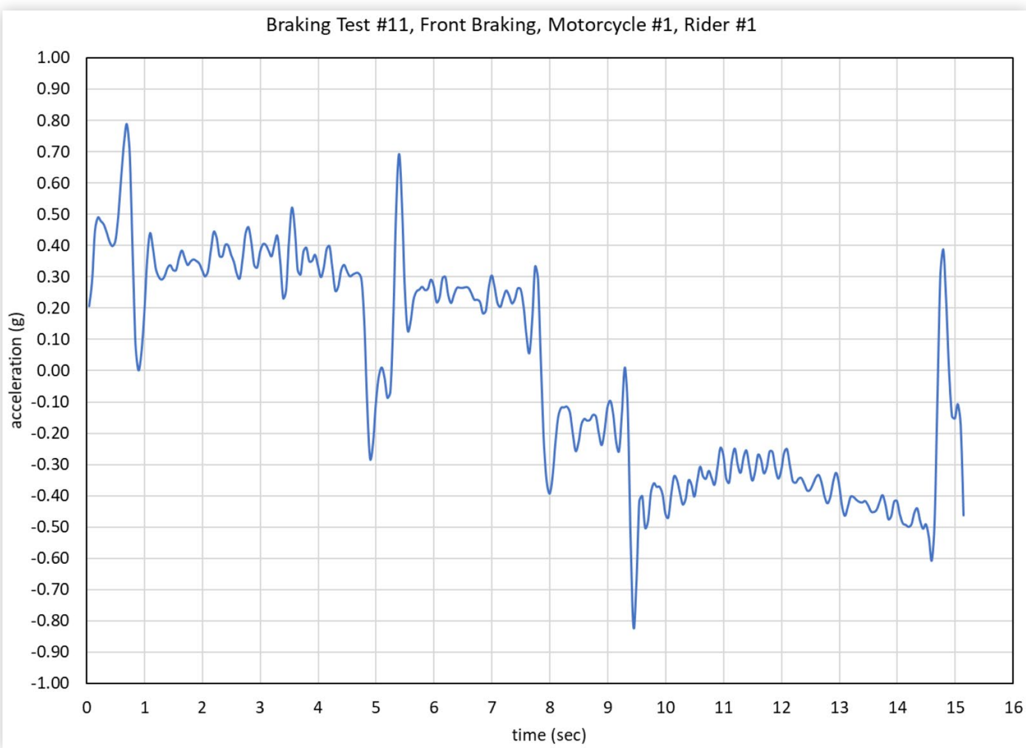


FIGURE A23 Speed, Braking Test #12, Rear Brake Pedal Only

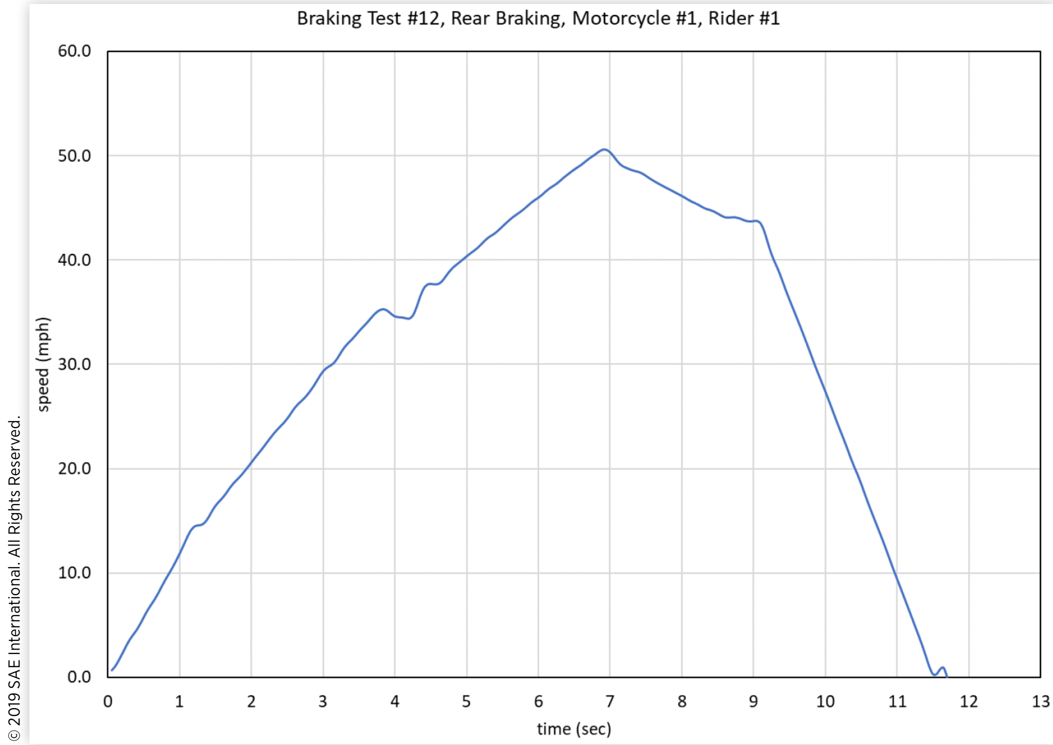


FIGURE A24 Acceleration, Braking Test #12, Rear Brake Pedal Only

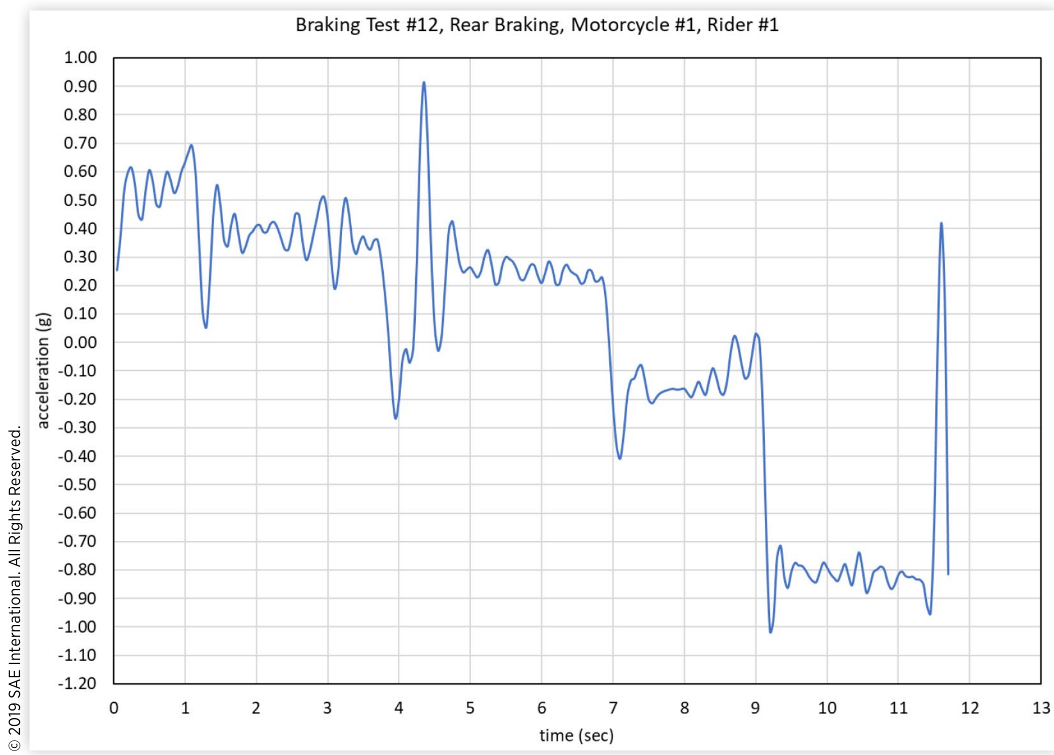


FIGURE A25 Speed, Braking Test #13, Front and Rear Braking Combined

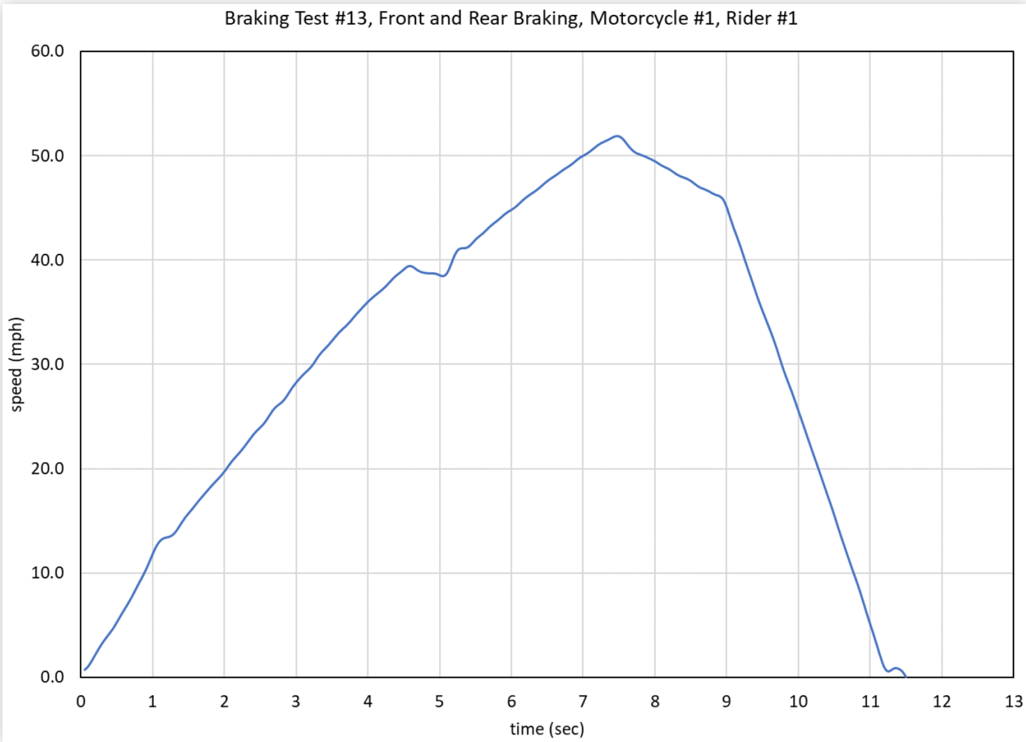


FIGURE A26 Acceleration, Braking Test #13, Front and Rear Braking Combined

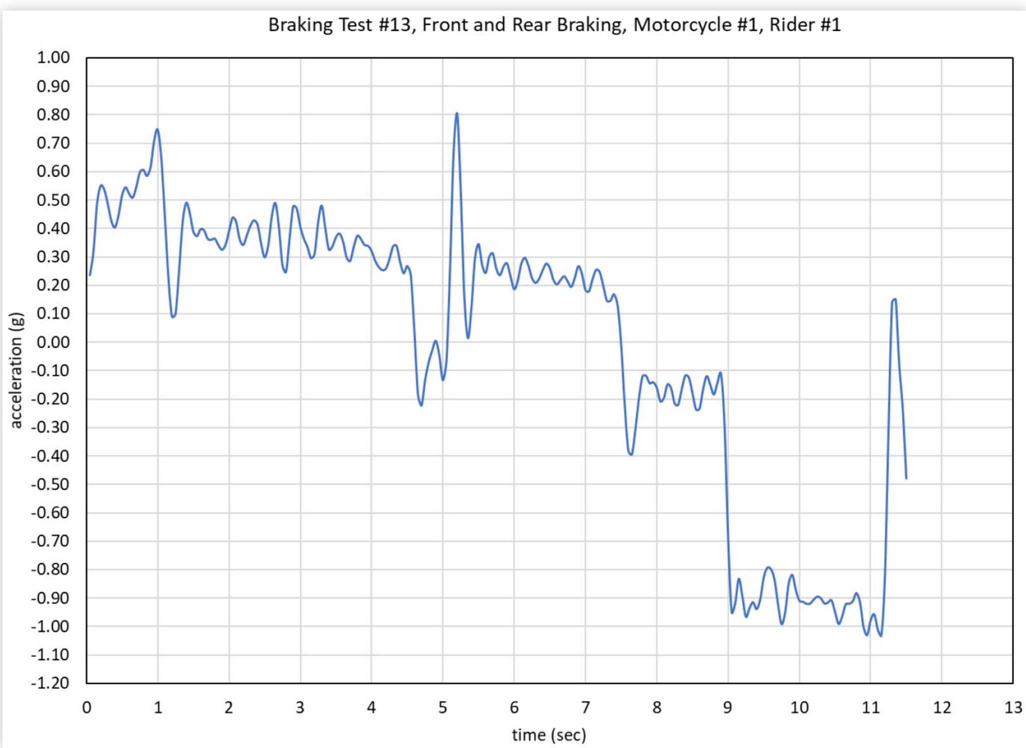


FIGURE A27 Speed, Braking Test #14, Front Braking Only

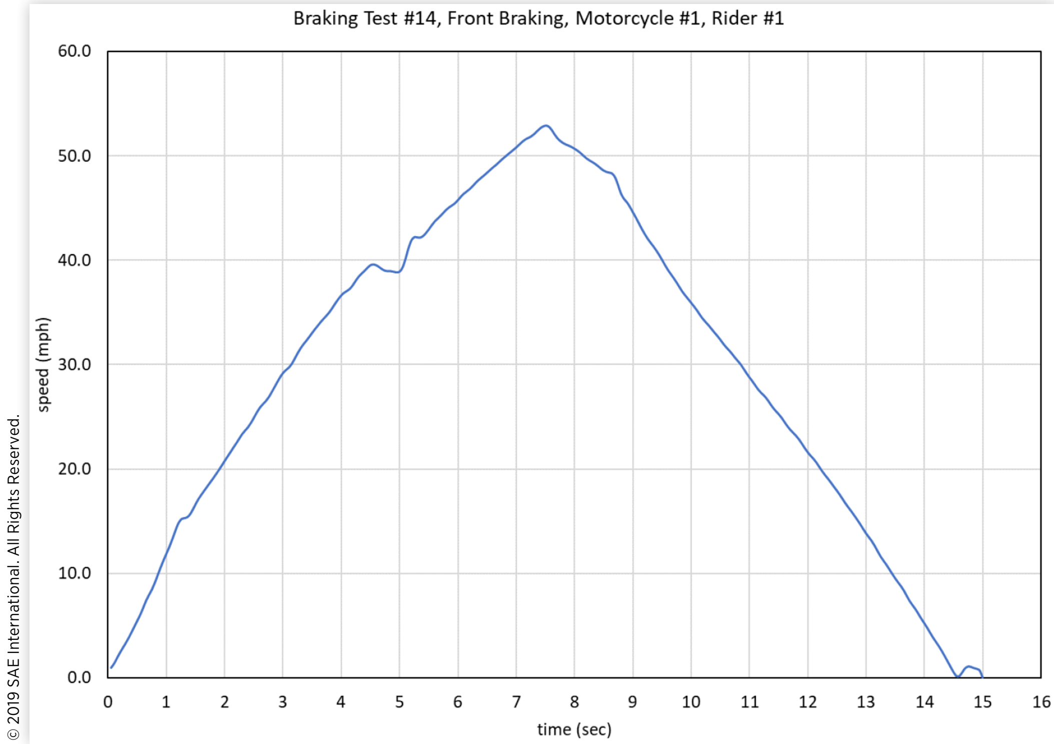


FIGURE A28 Acceleration, Braking Test #14, Front Braking Only

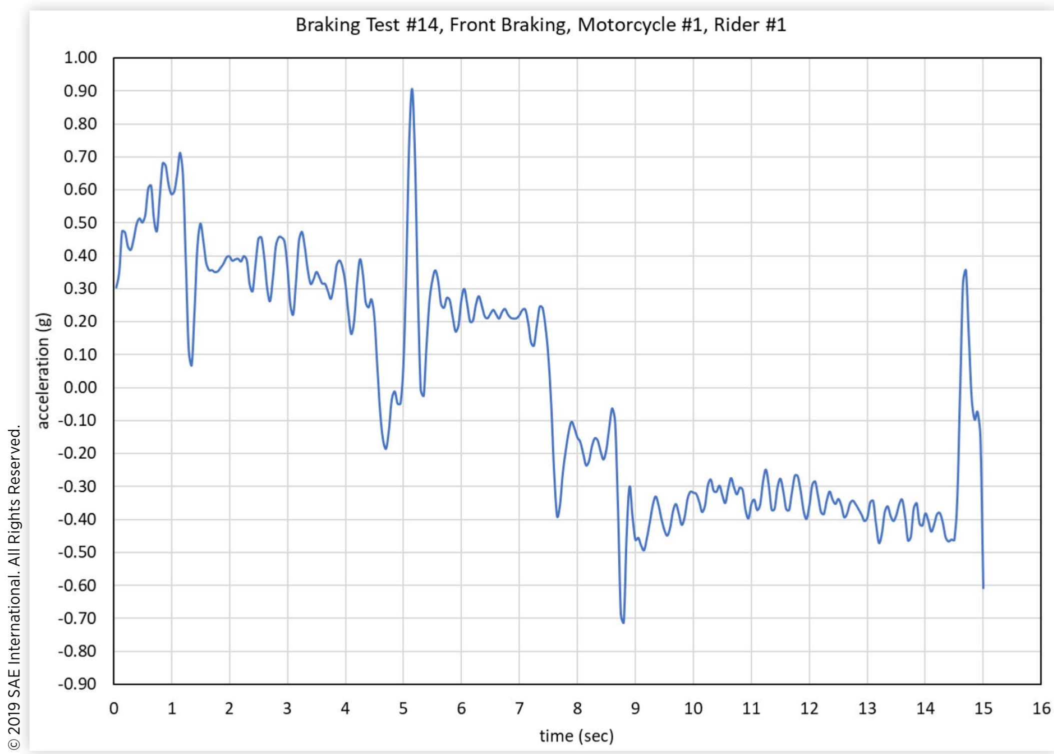


FIGURE A29 Speed, Braking Test #15, Rear Brake Pedal Only

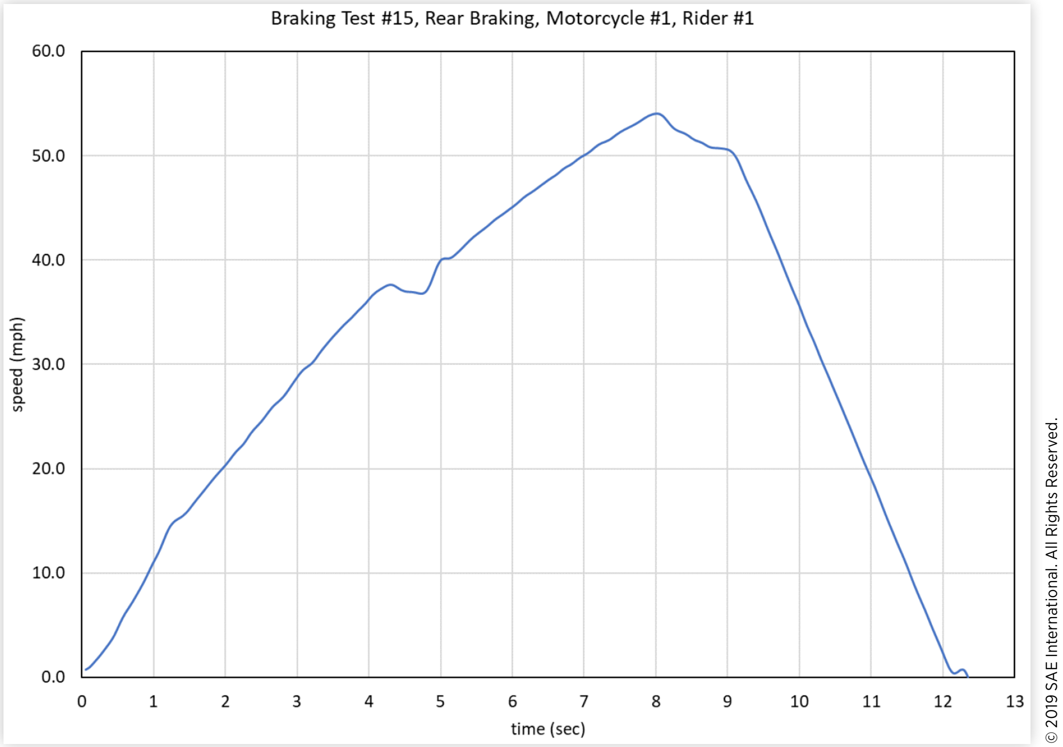


FIGURE A30 Acceleration, Braking Test #15, Rear Brake Pedal Only

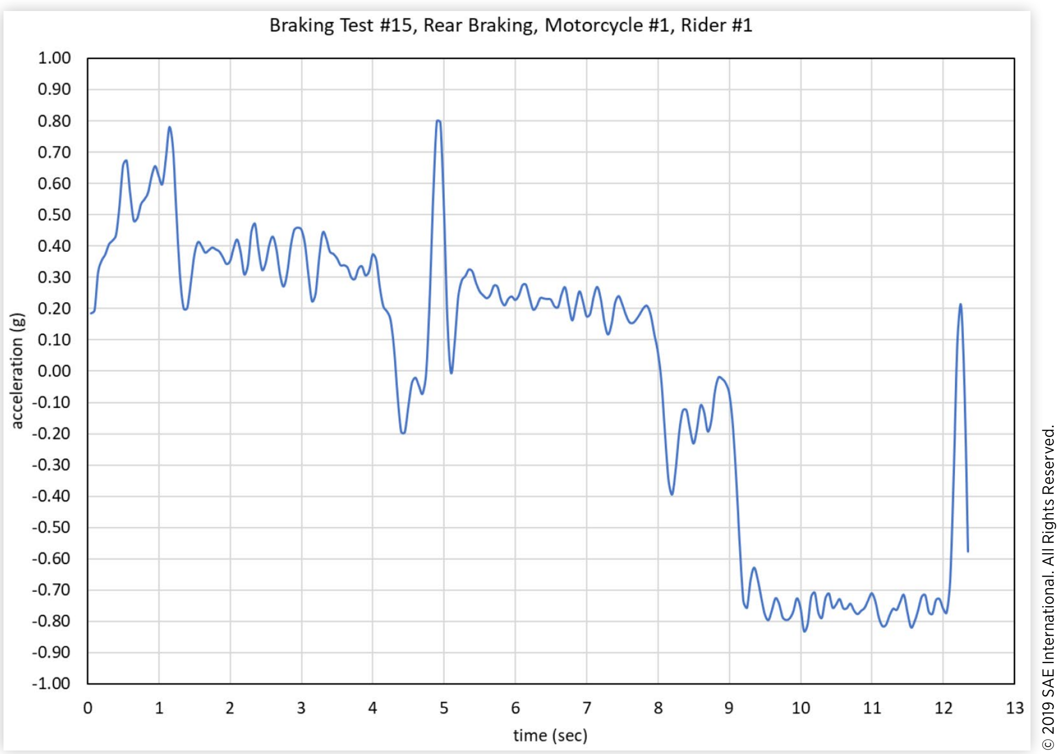


FIGURE A31 Speed, Braking Test #16, Front and Rear Braking Combined

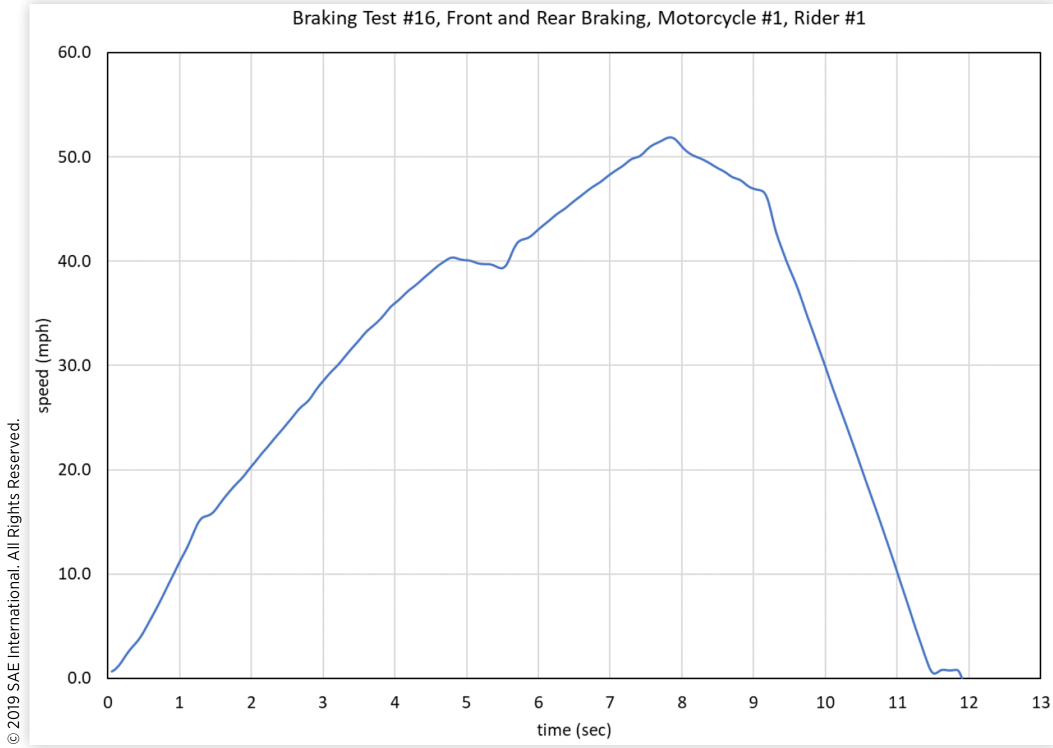


FIGURE A32 Acceleration, Braking Test #16, Front and Rear Braking Combined

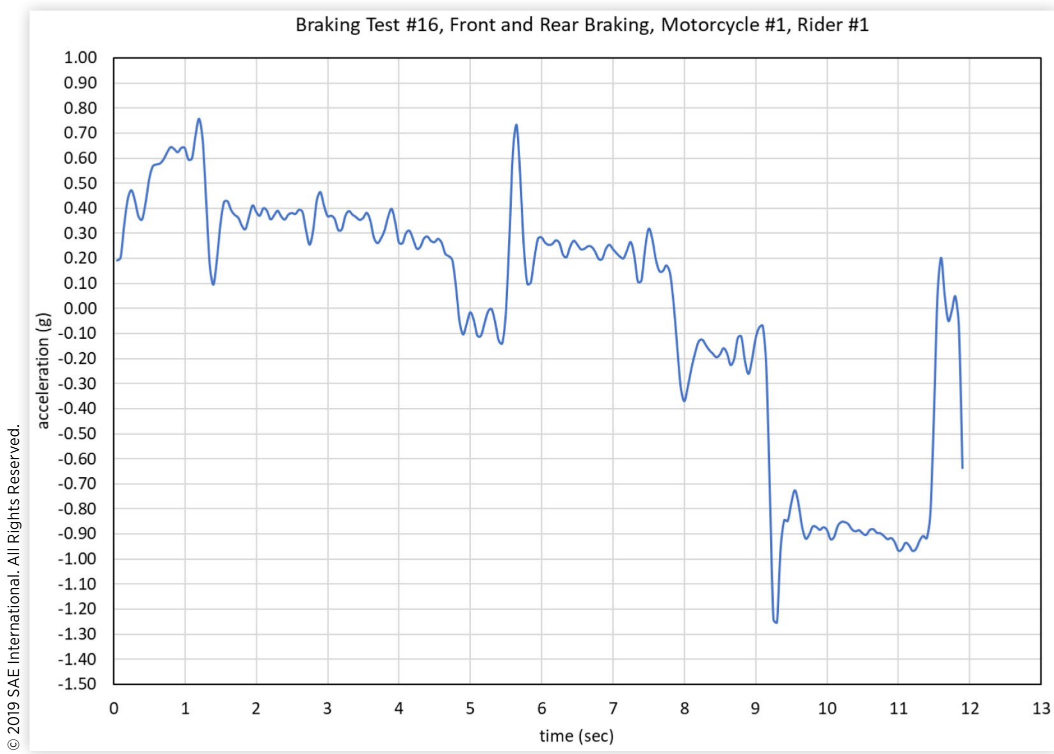


FIGURE A33 Speed, Braking Test #17, Front Braking Only

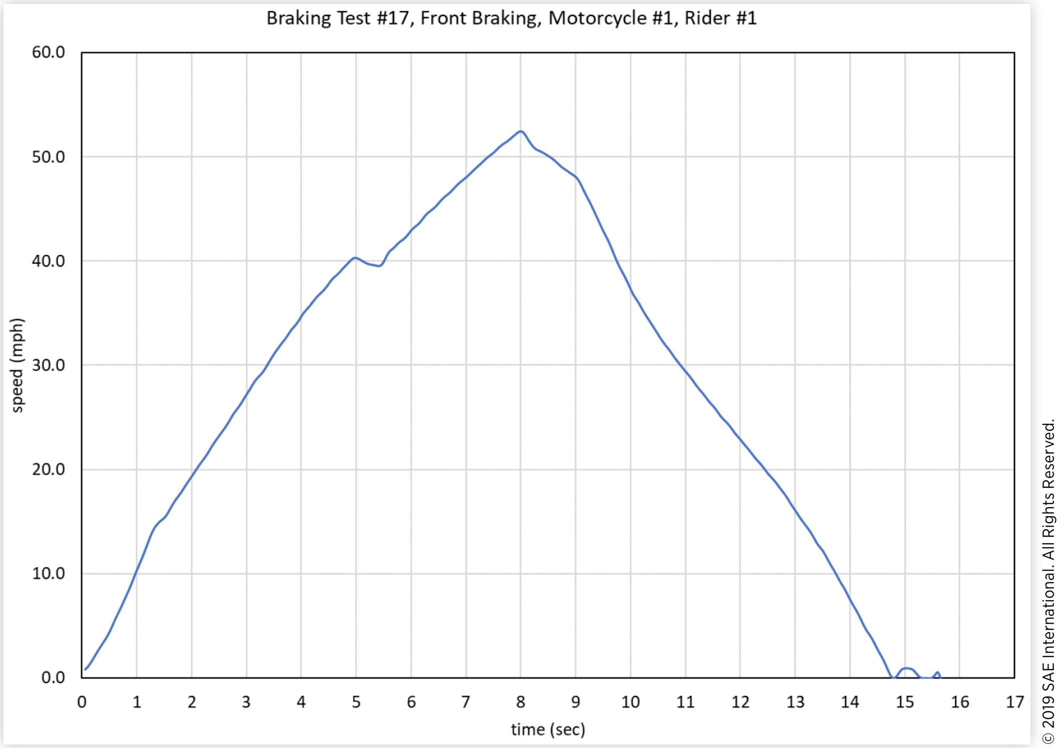


FIGURE A34 Acceleration, Braking Test #17, Front Braking Only

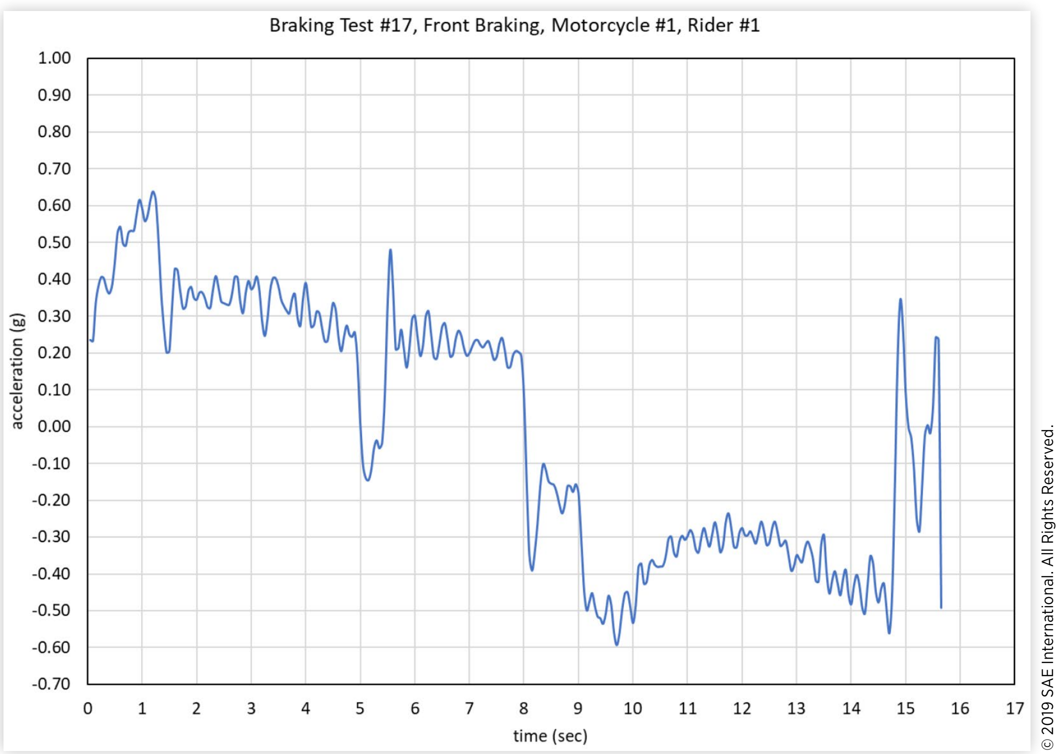


FIGURE A35 Speed, Braking Test #18, Rear Brake Pedal Only

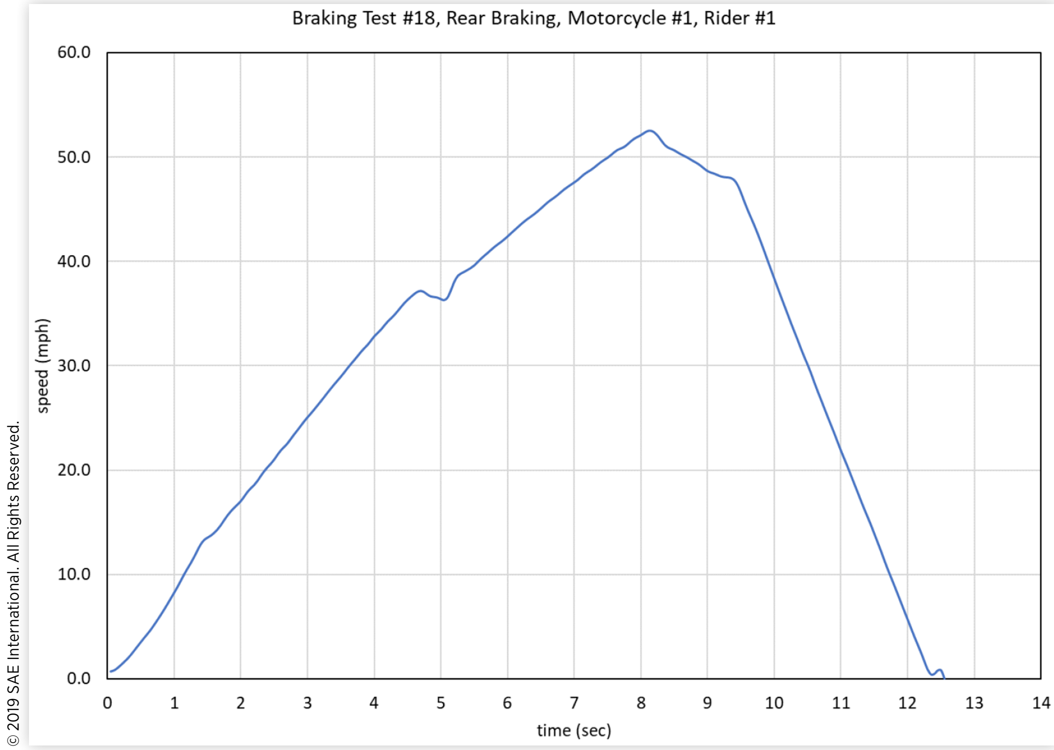


FIGURE A36 Acceleration, Braking Test #18, Rear Brake Pedal Only

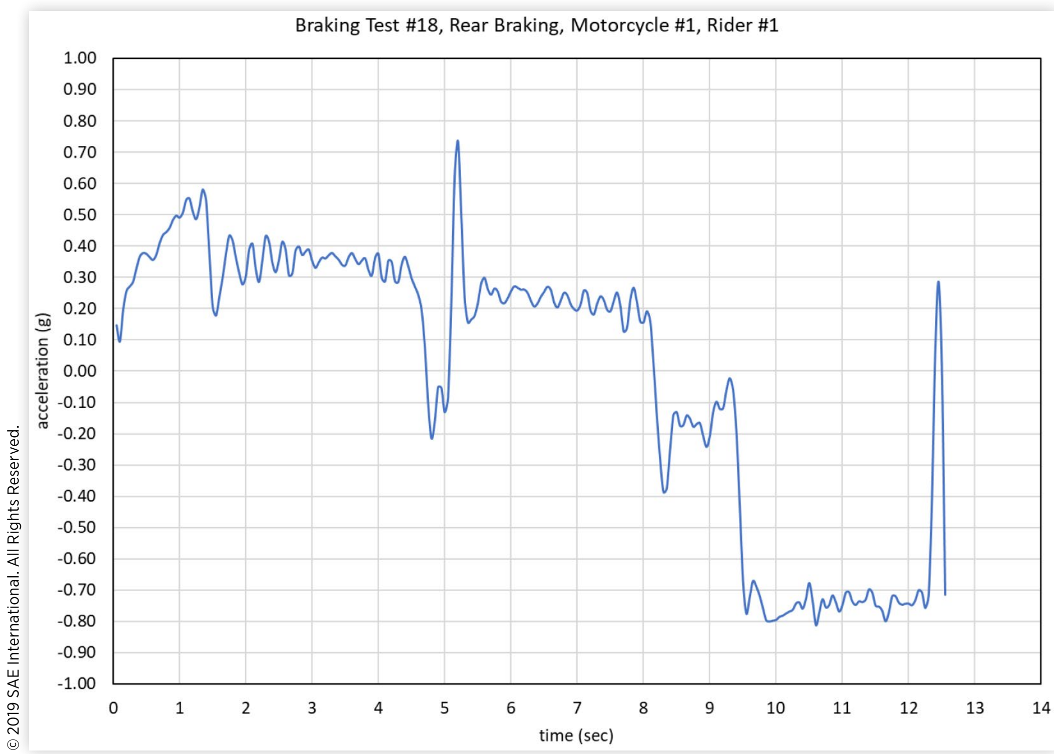


FIGURE A37 Speed, Braking Test #19, Front and Rear Braking Combined

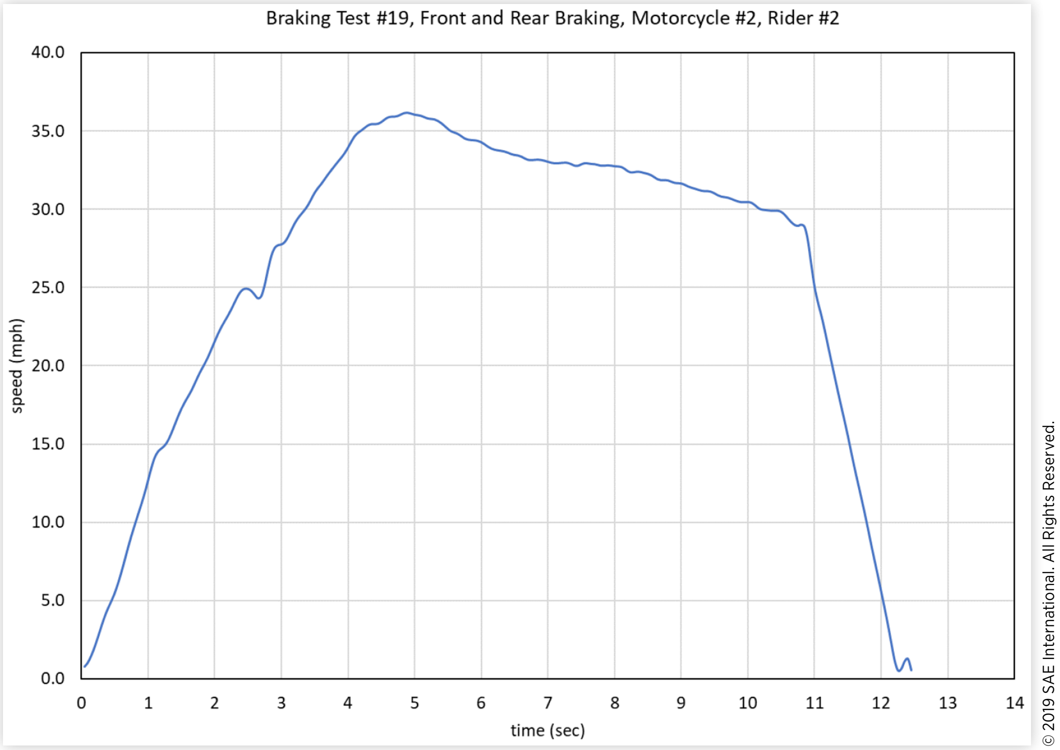


FIGURE A38 Acceleration, Braking Test #19, Front and Rear Braking Combined

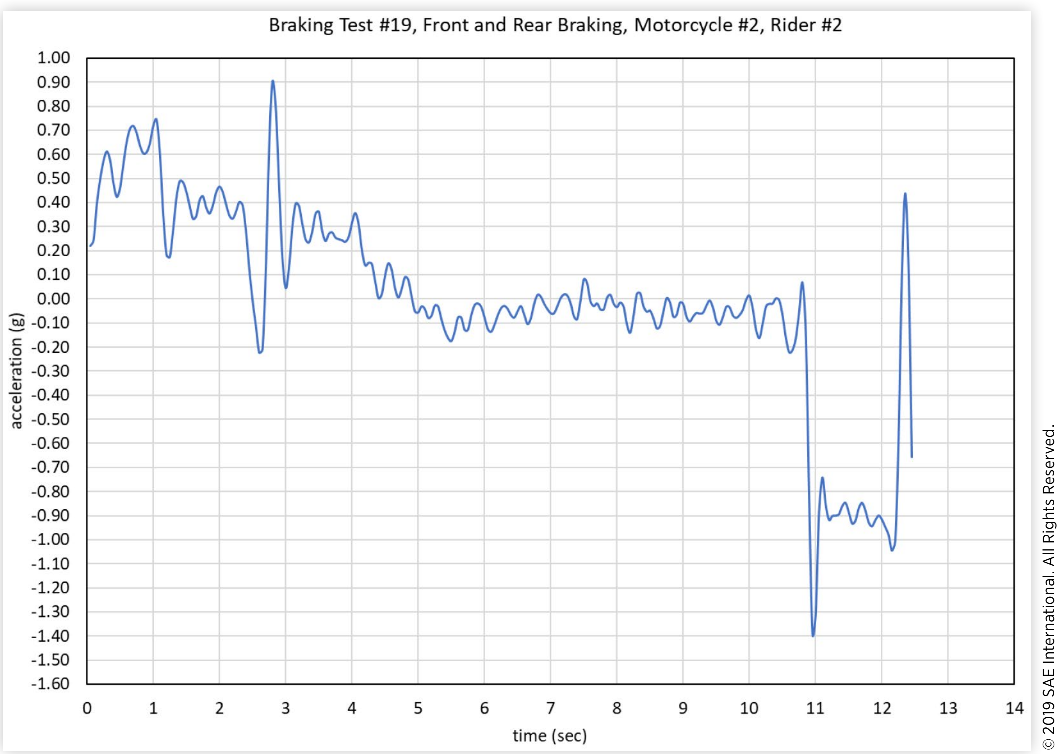


FIGURE A39 Speed, Braking Test #20, Front Braking Only

FIGURE A40 Acceleration, Braking Test #20, Front Braking Only

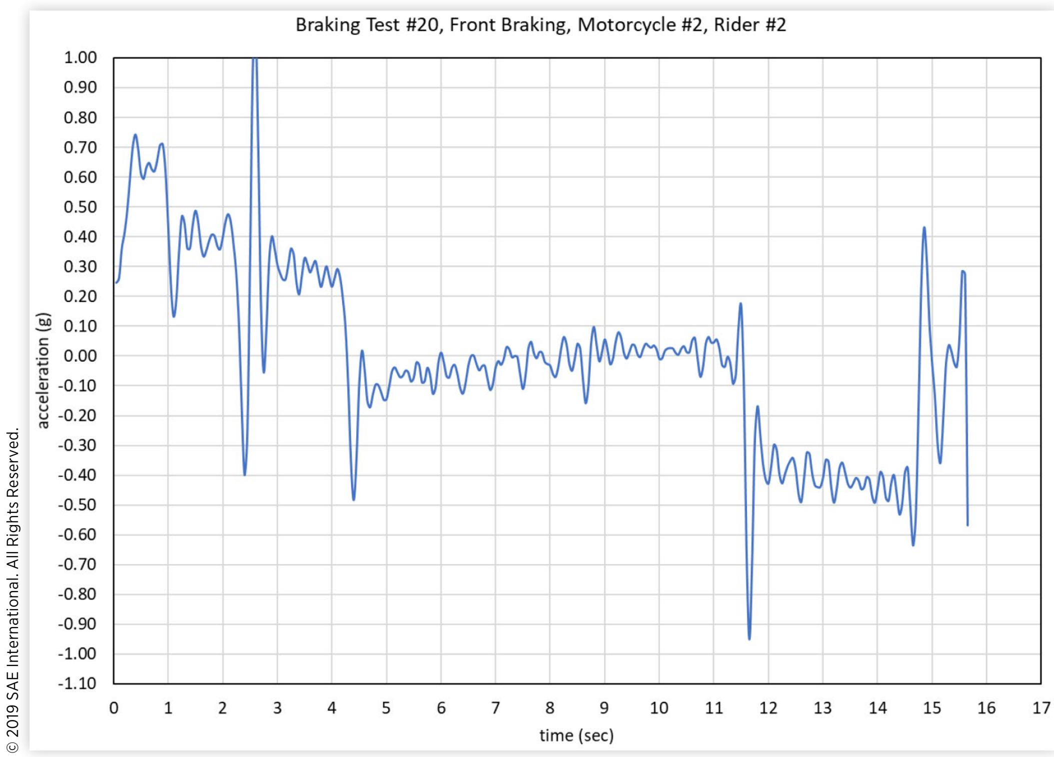


FIGURE A41 Speed, Braking Test #21, Rear Brake Pedal Only

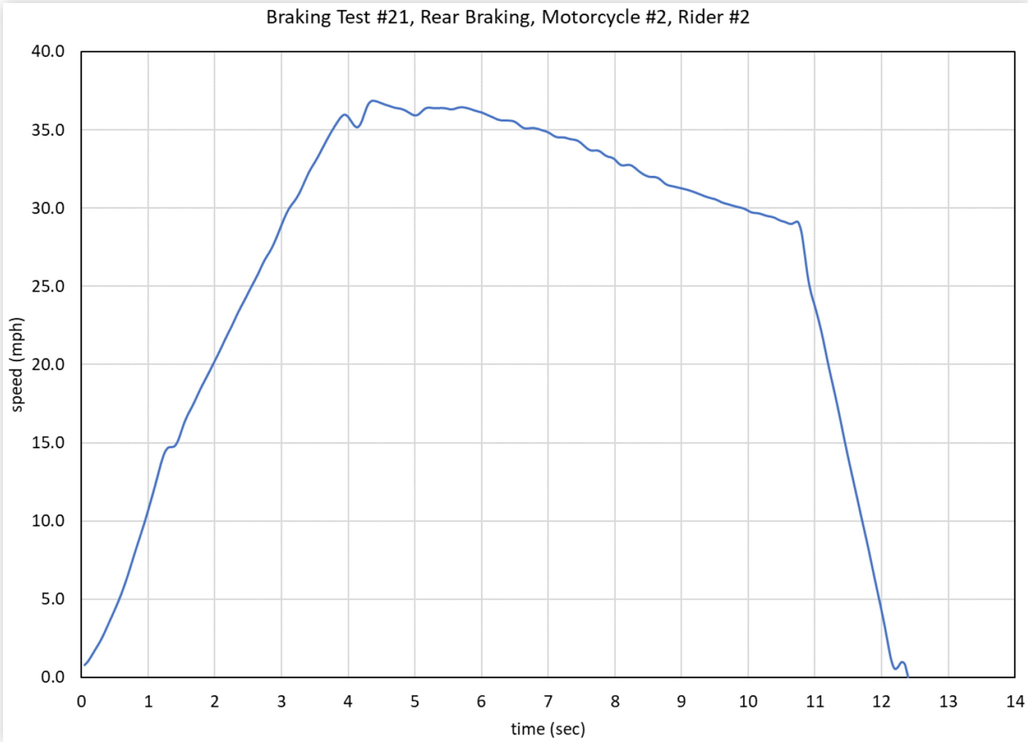


FIGURE A42 Acceleration, Braking Test #21, Rear Brake Pedal Only

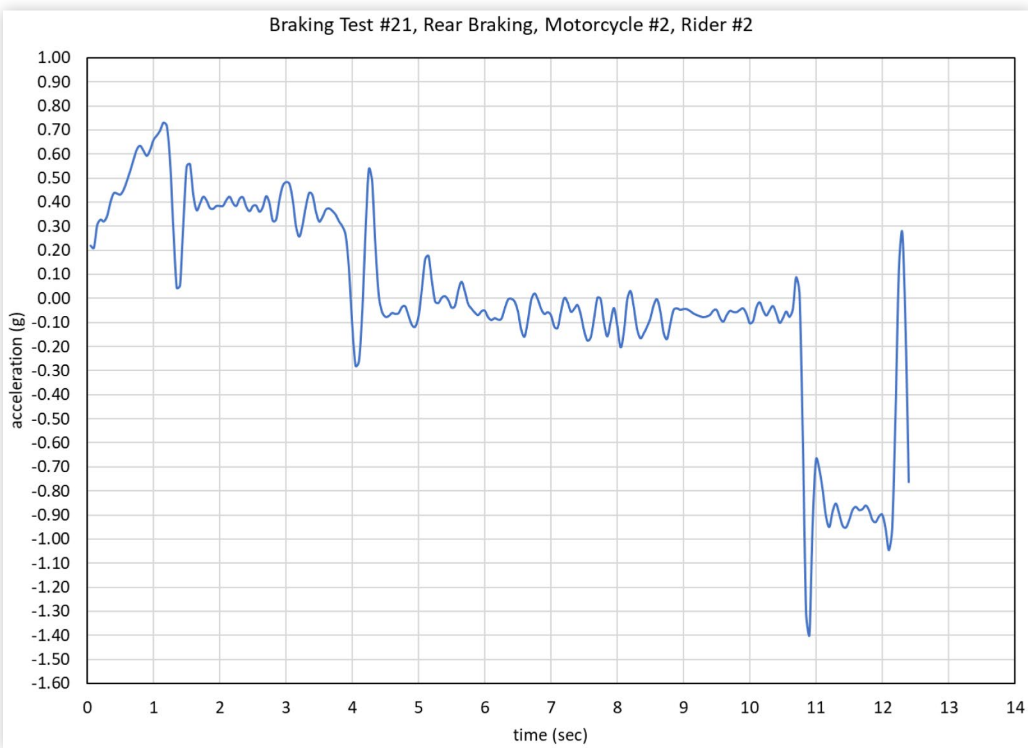


FIGURE A43 Speed, Braking Test #22, Front and Rear Braking Combined

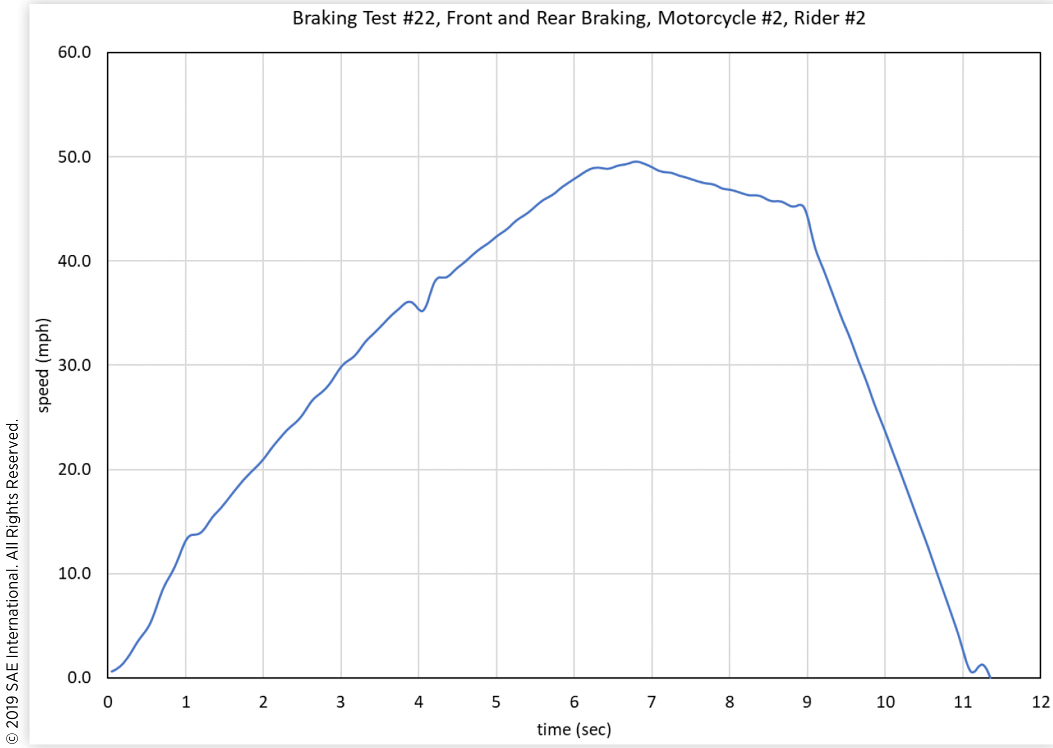


FIGURE A44 Acceleration, Braking Test #22, Front and Rear Braking Combined

FIGURE A45 Speed, Braking Test #23, Rear Brake Pedal Only

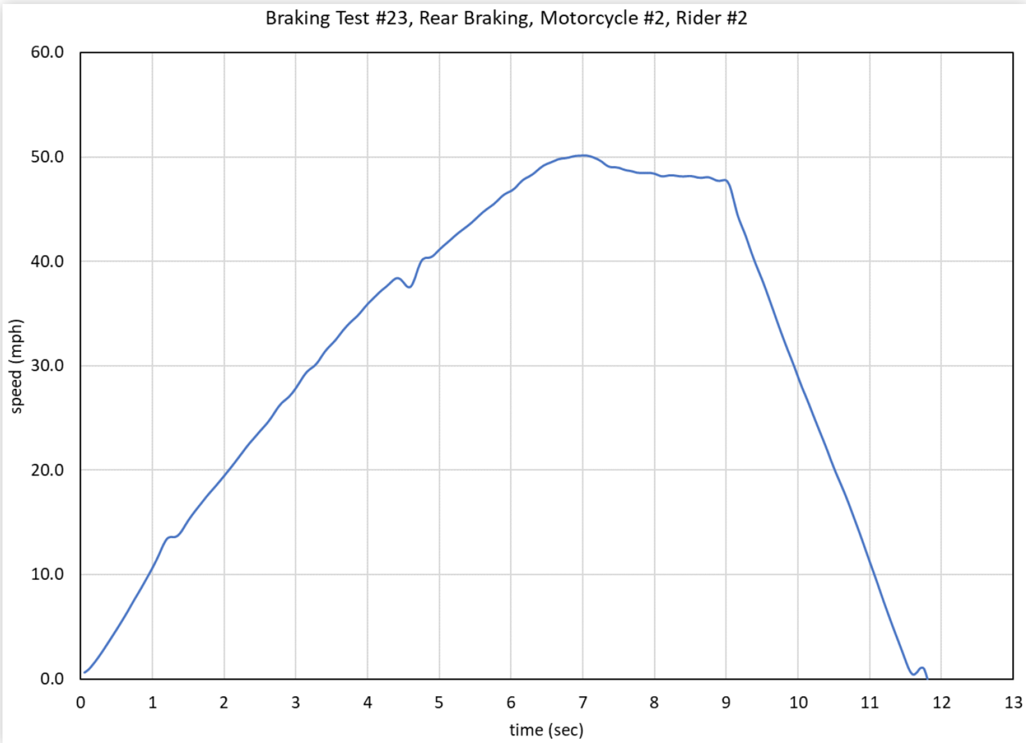


FIGURE A46 Acceleration, Braking Test #23, Rear Brake Pedal Only

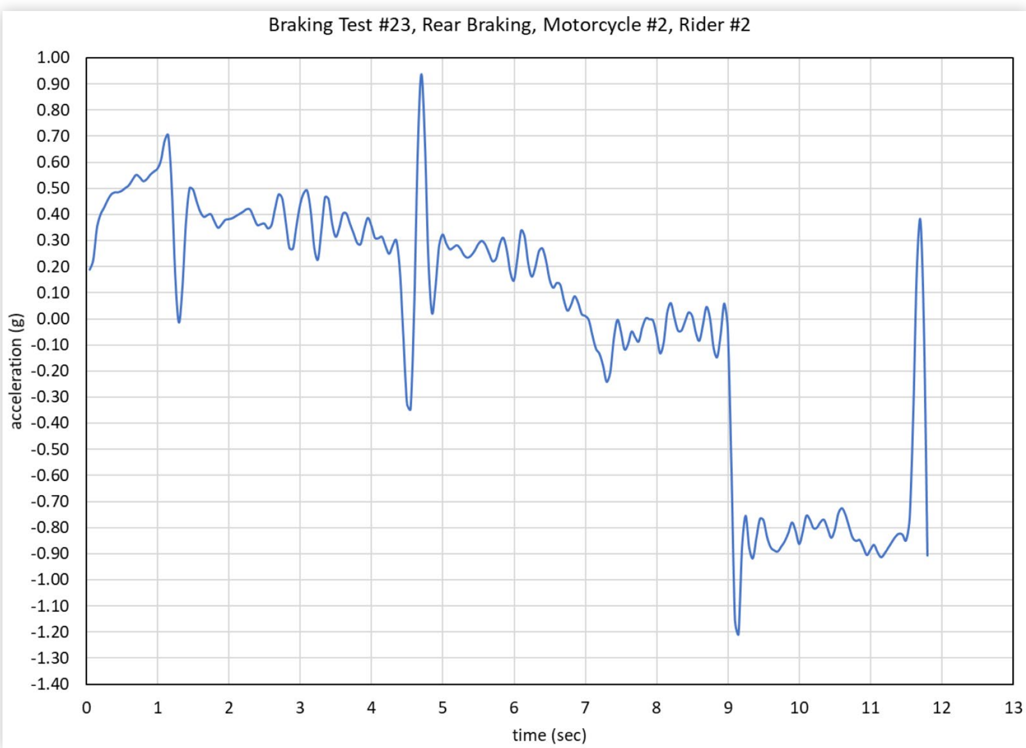


FIGURE A47 Speed, Braking Test #24, Front and Rear Braking Combined with Ballast

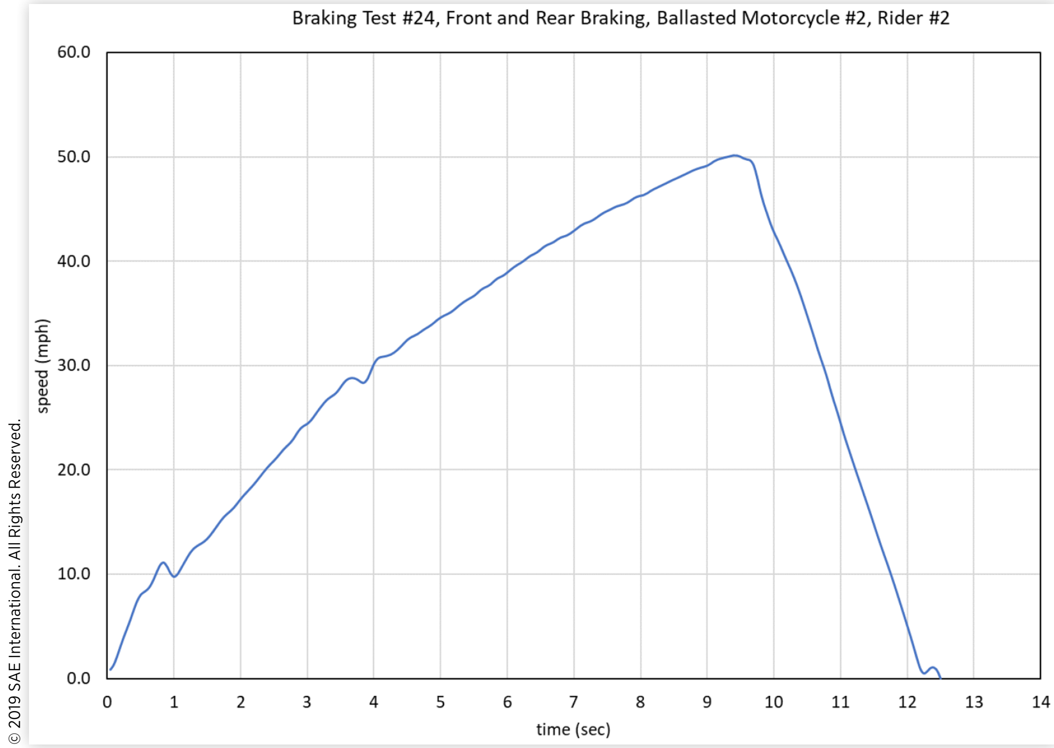


FIGURE A48 Acceleration, Braking Test #24, Front and Rear Braking Combined with Ballast

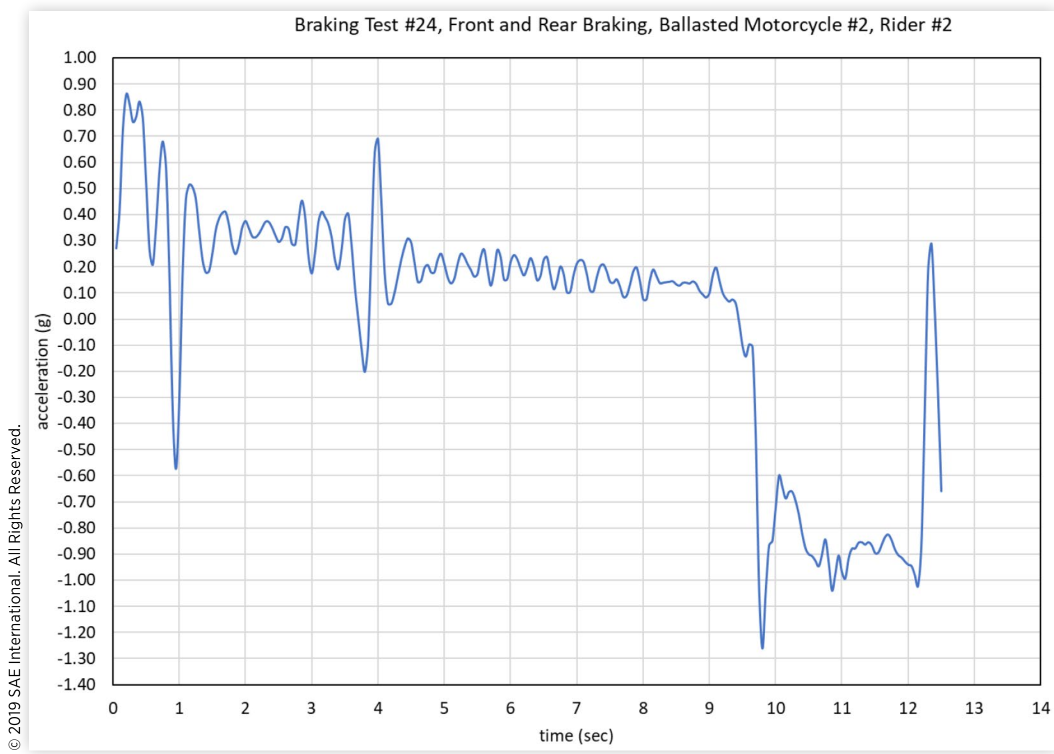


FIGURE A49 Speed, Braking Test #25, Rear Brake Pedal Only with Ballast

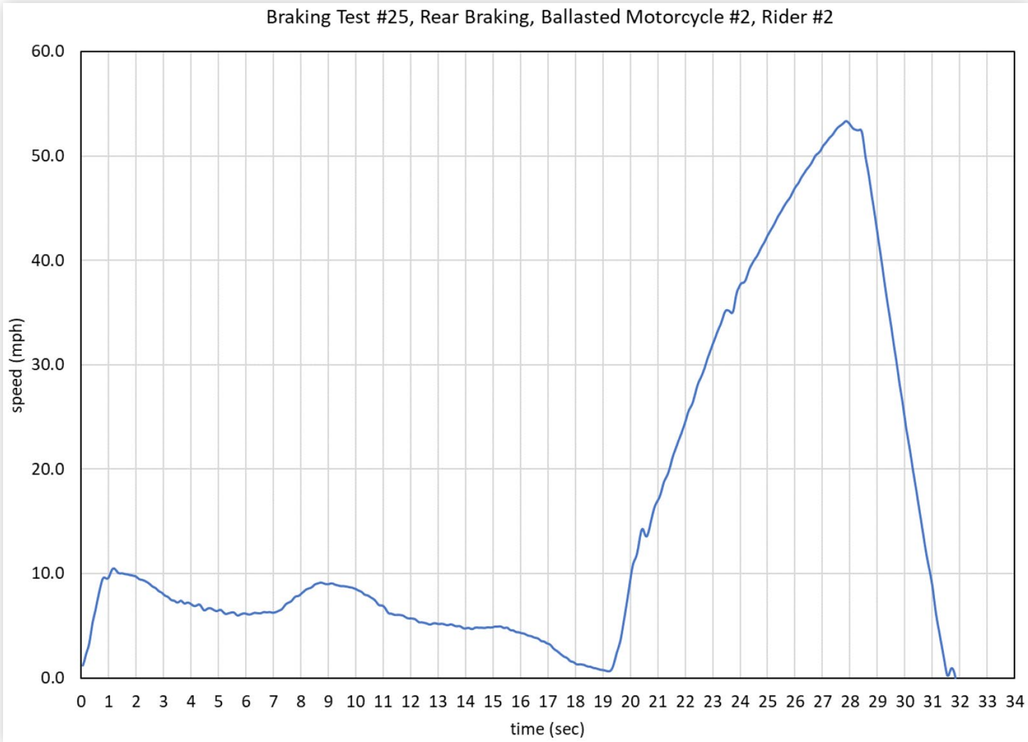
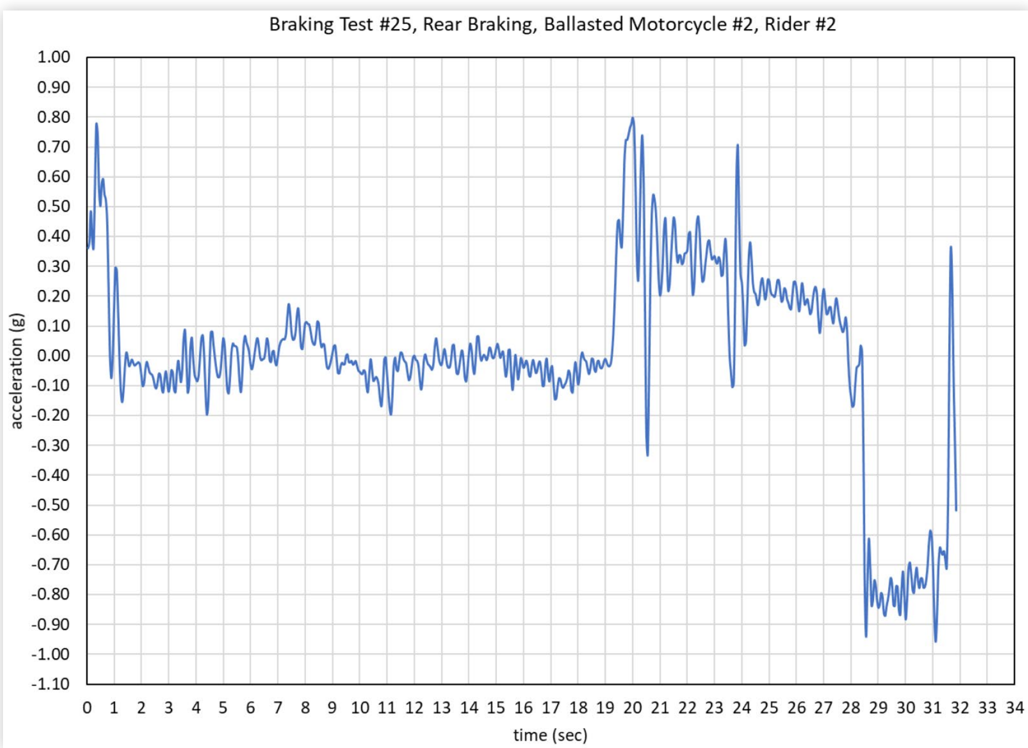


FIGURE A50 Acceleration, Braking Test #25, Rear Brake Pedal Only with Ballast



Appendix B - Swerve Tests

FIGURE B1 Speed, Swerve Test #1

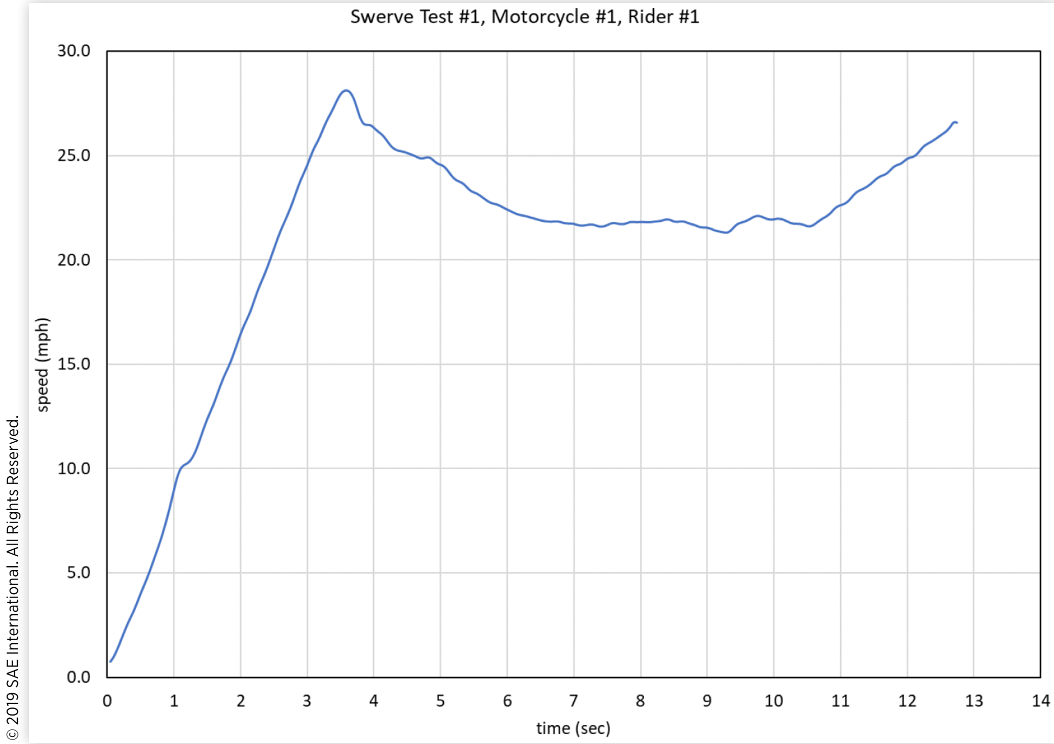


FIGURE B2 Lateral Acceleration, Swerve Test #1

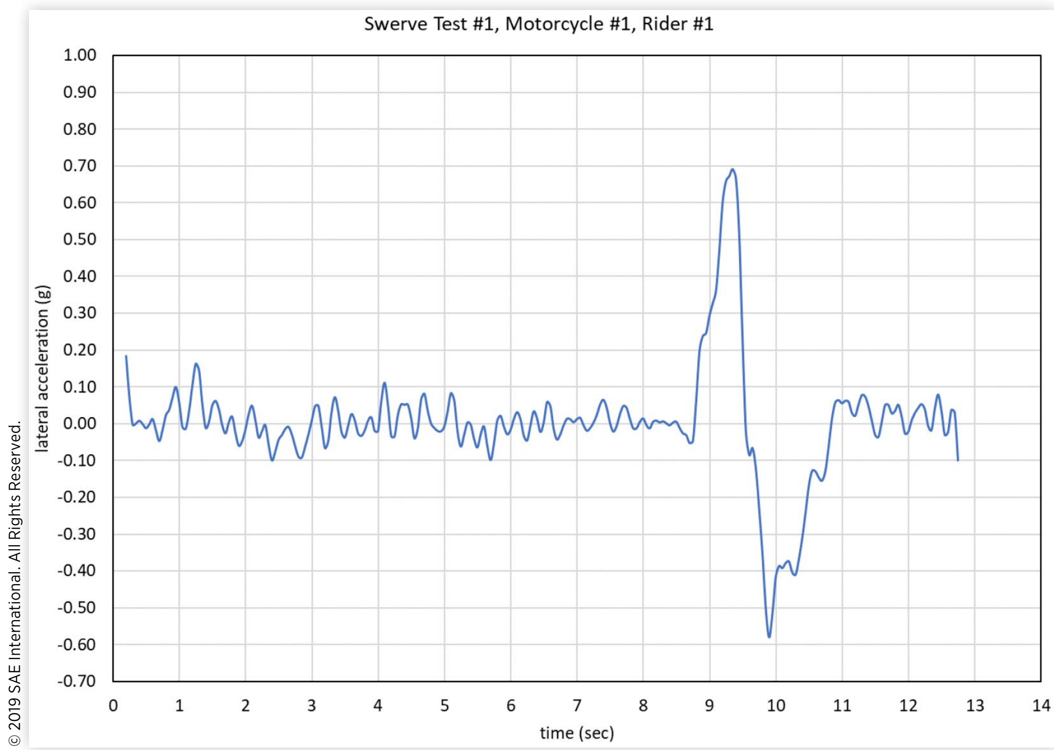


FIGURE B3 Heading, Swerve Test #1

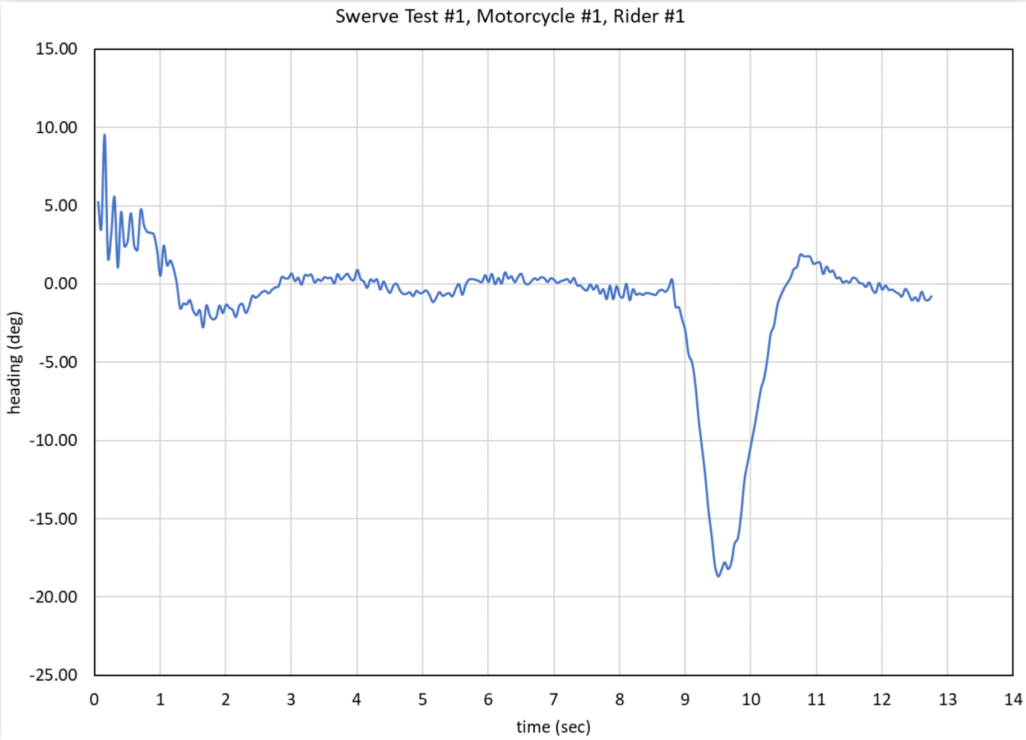


FIGURE B4 Speed, Swerve Test #2

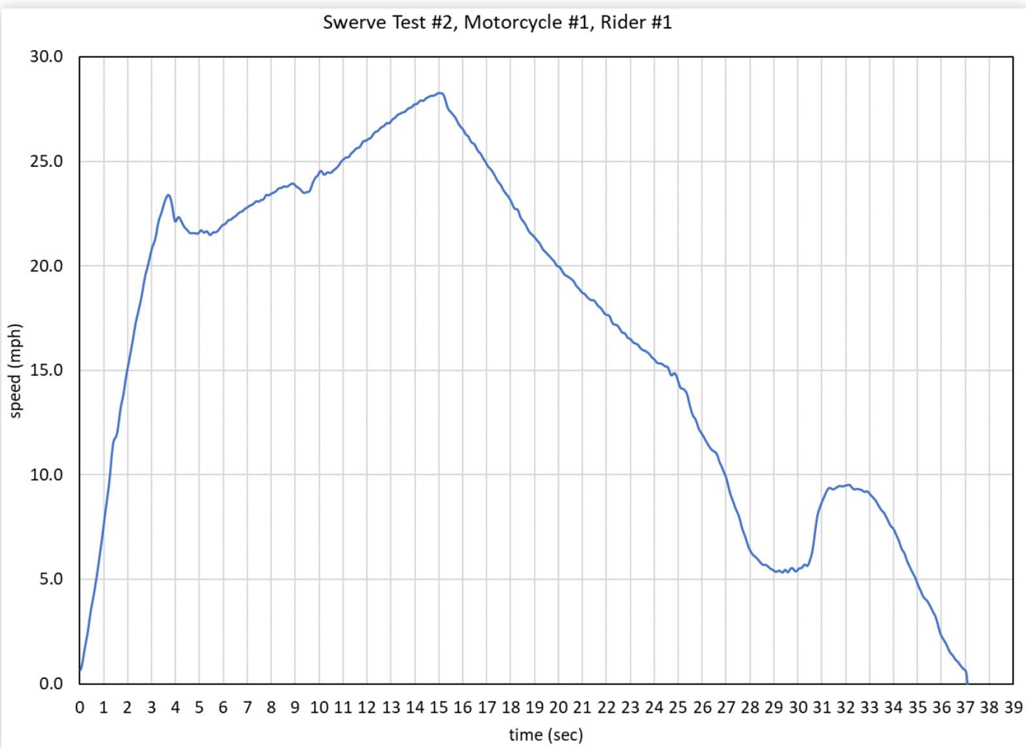


FIGURE B5 Lateral Acceleration, Swerve Test #2

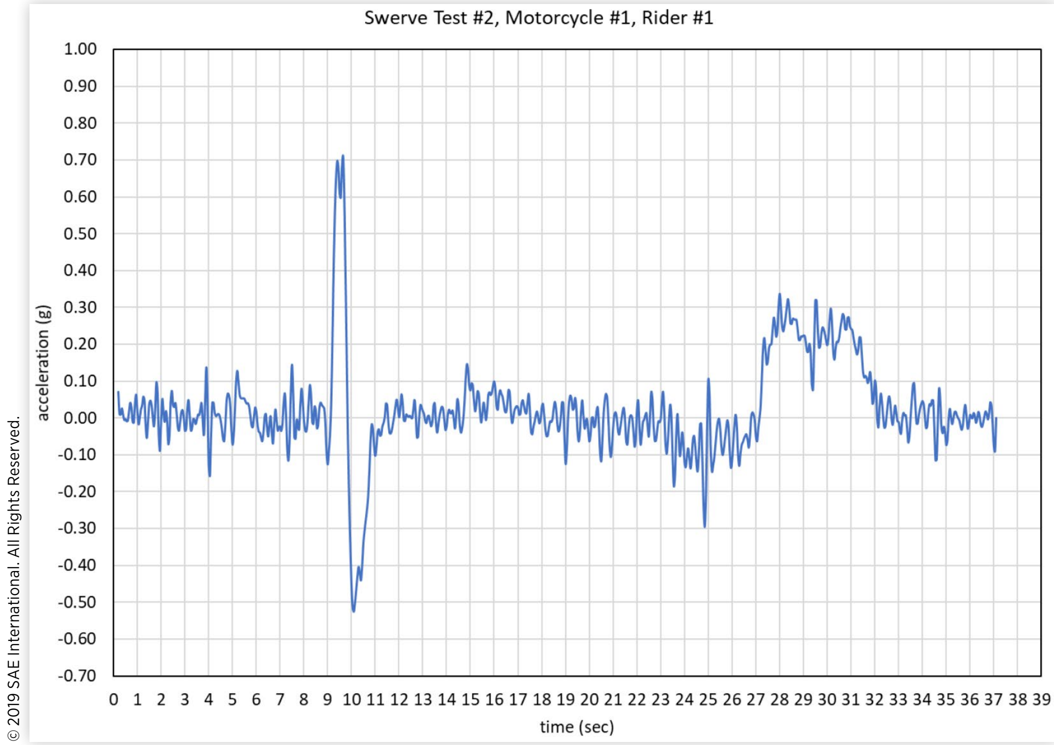


FIGURE B6 Heading, Swerve Test #2

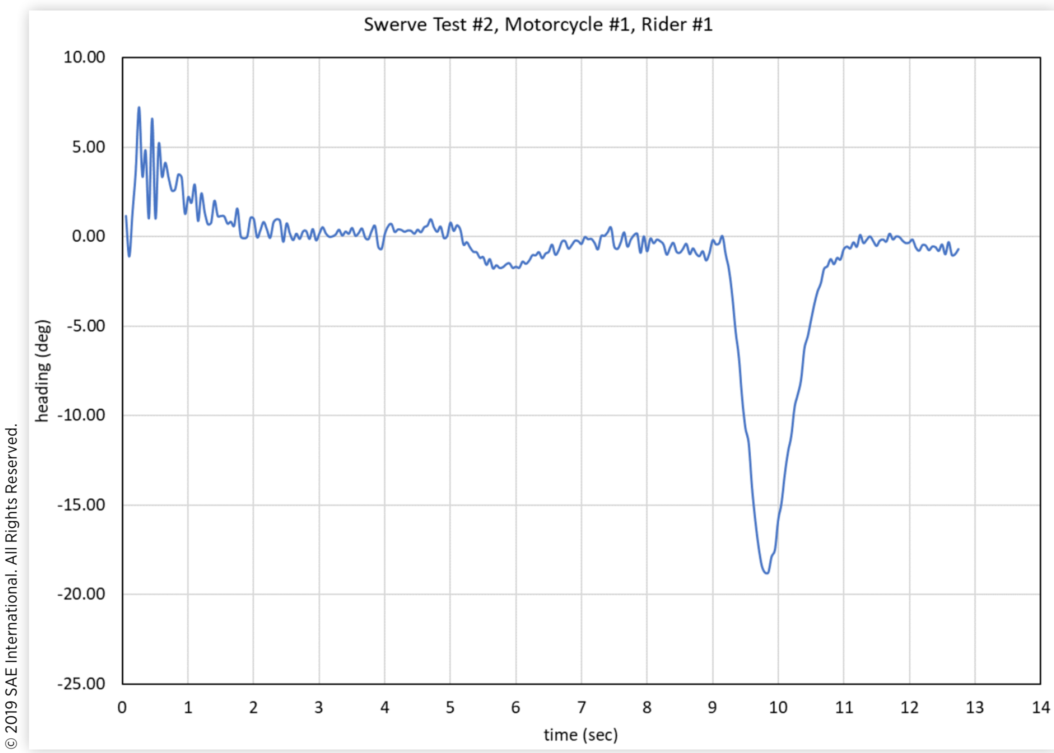


FIGURE B7 Speed, Swerve Test #3

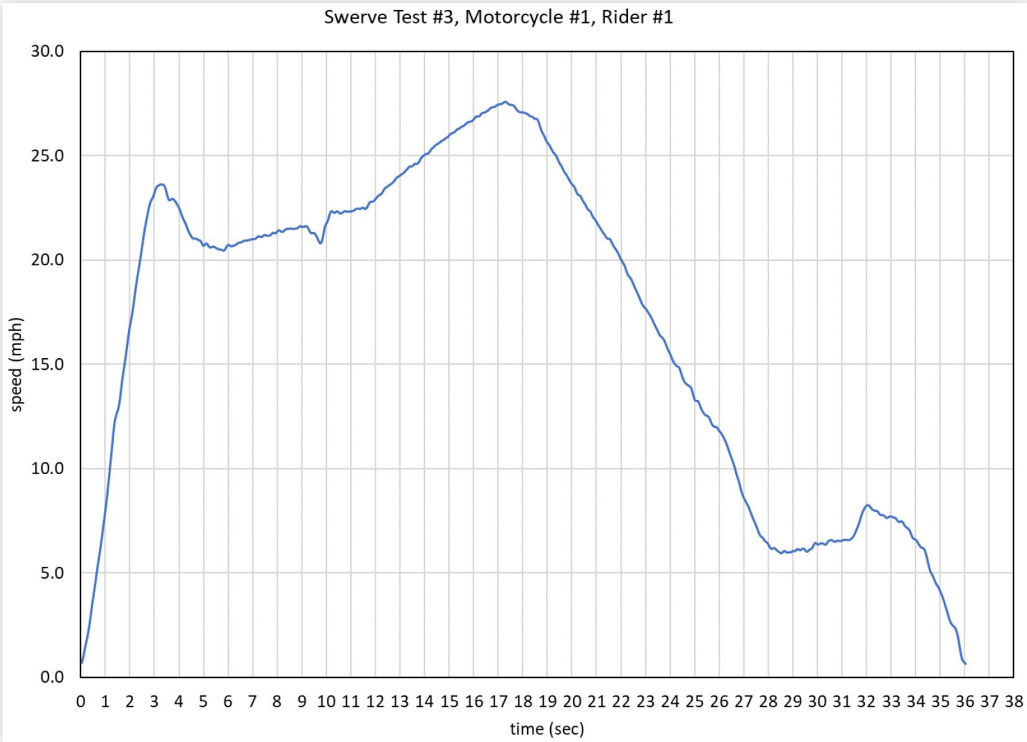


FIGURE B8 Lateral Acceleration, Swerve Test #3

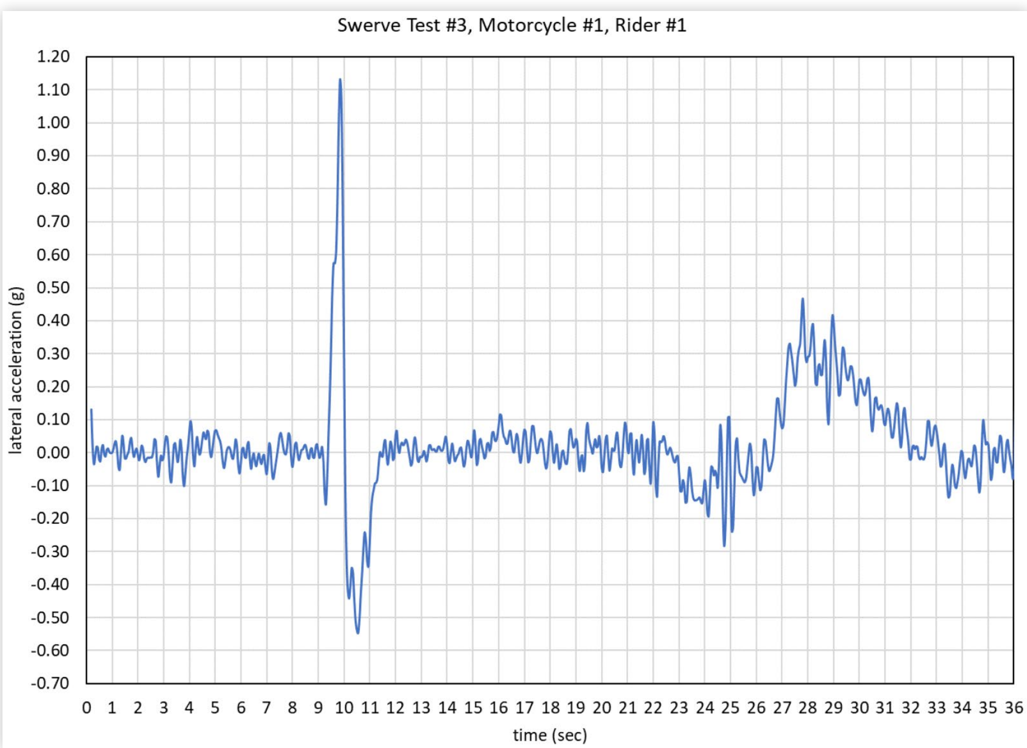


FIGURE B9 Heading, Swerve Test #3

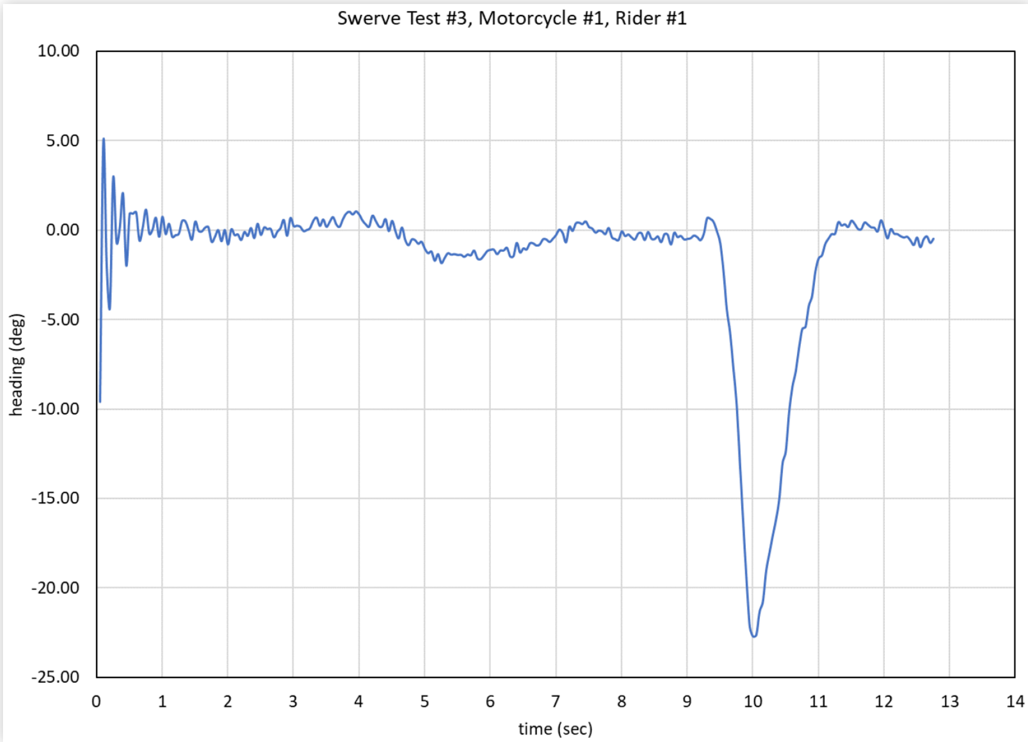


FIGURE B10 Speed, Swerve Test #4

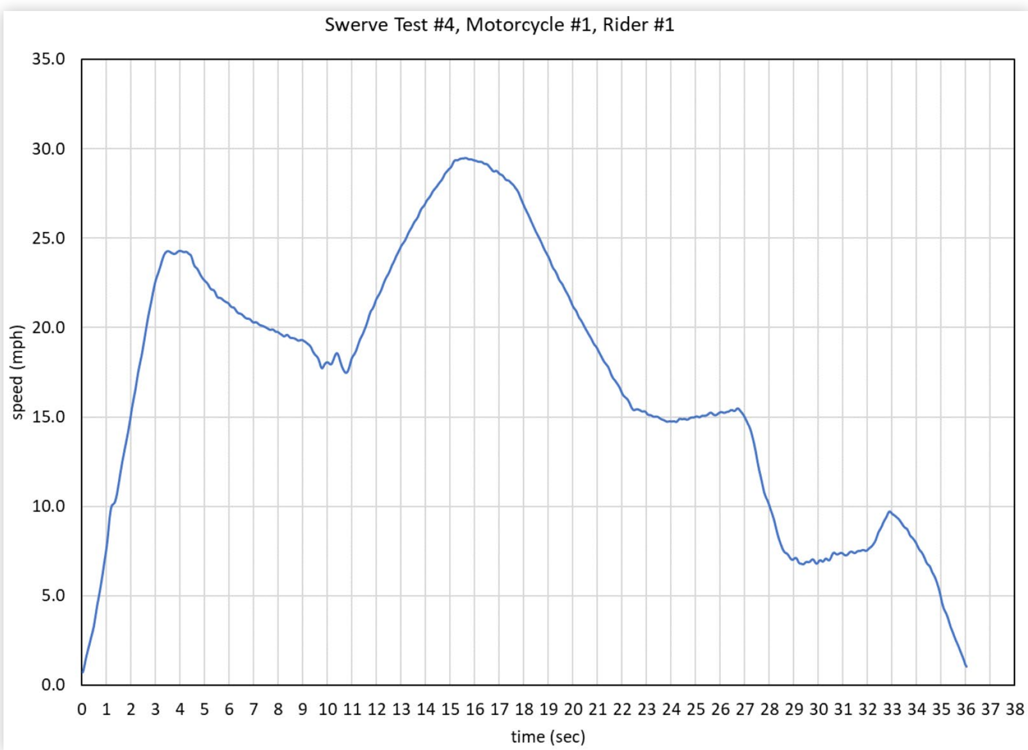


FIGURE B11 Lateral Acceleration, Swerve Test #4

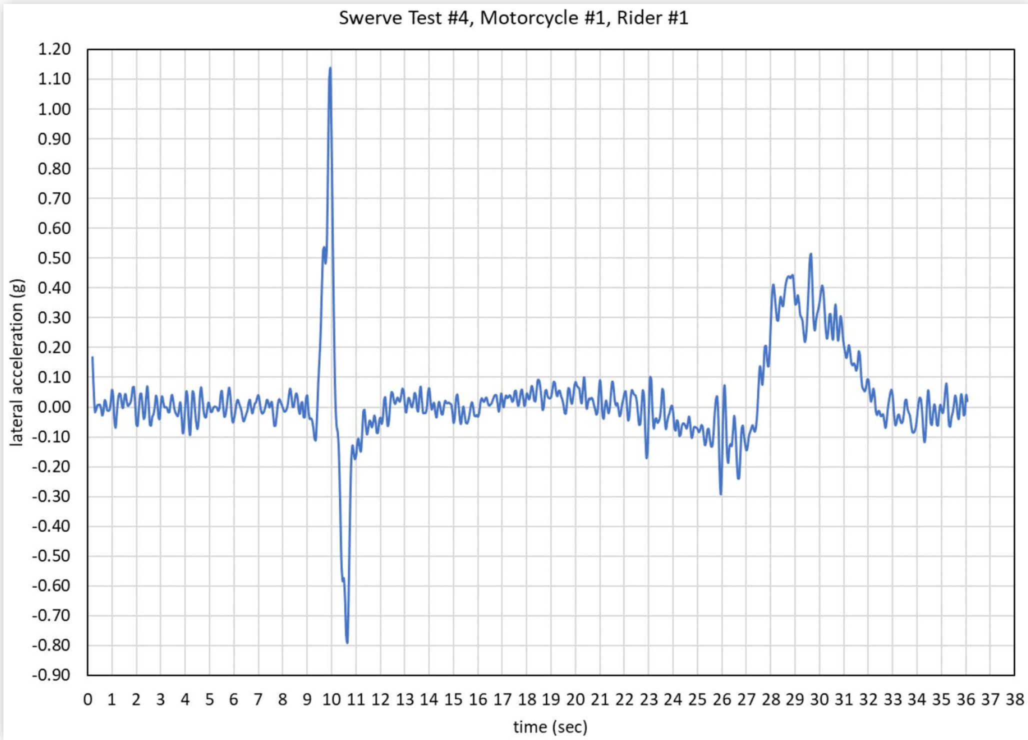


FIGURE B12 Heading, Swerve Test #4

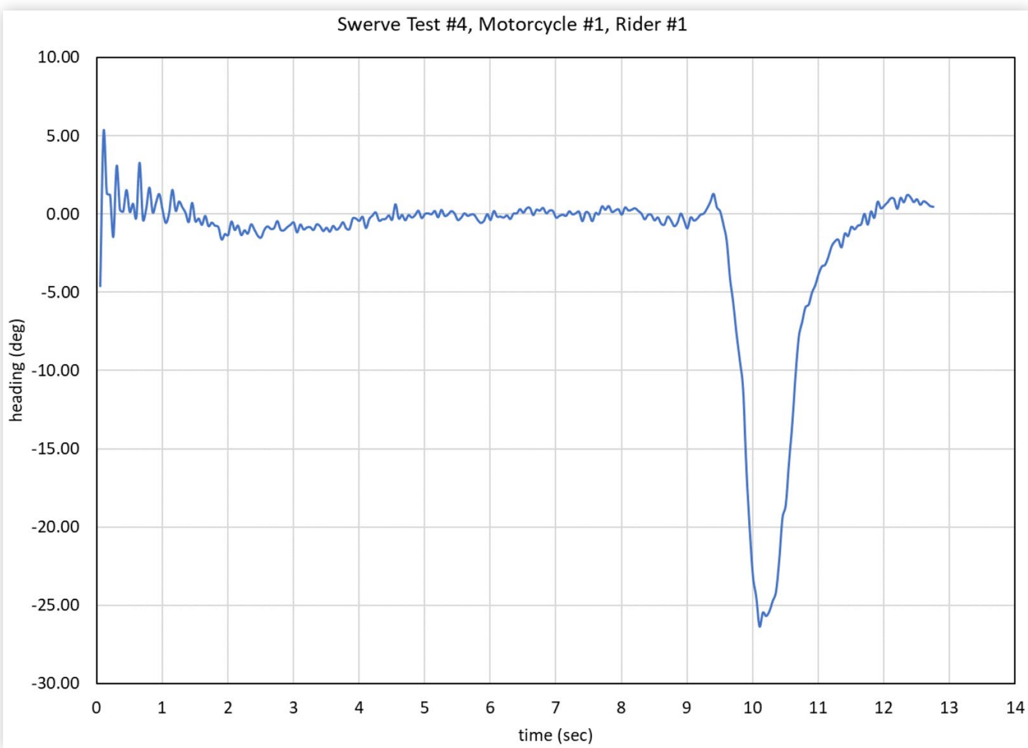


FIGURE B13 Speed, Swerve Test #5

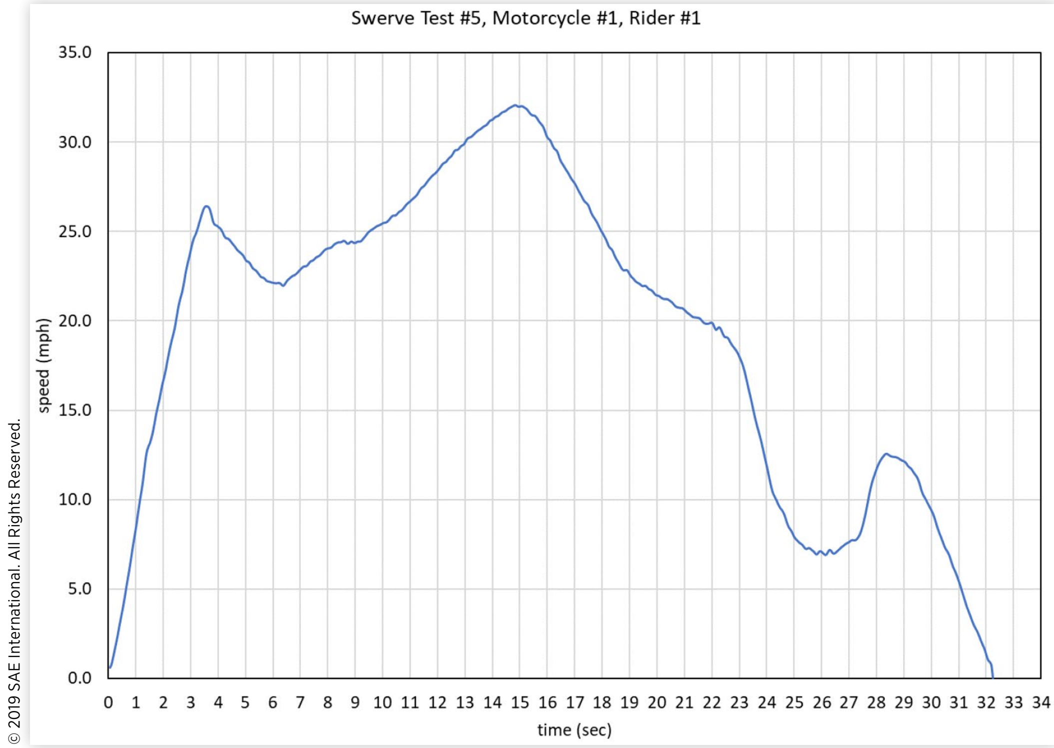


FIGURE B14 Lateral Acceleration, Swerve Test #5

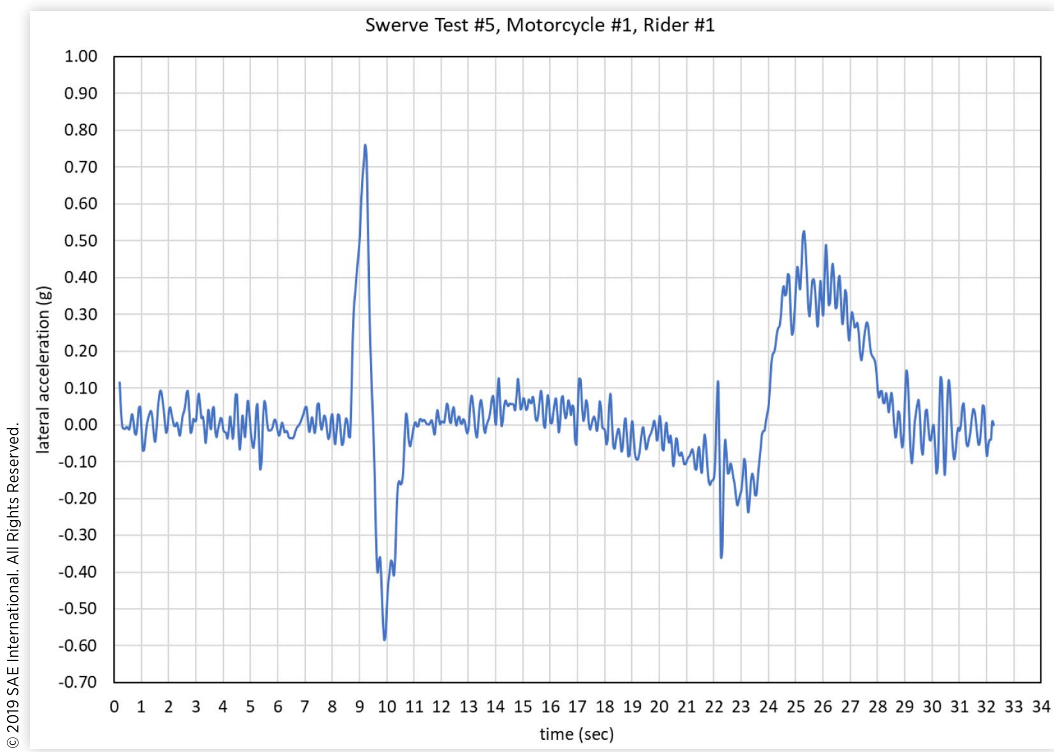


FIGURE B15 Heading, Swerve Test #5

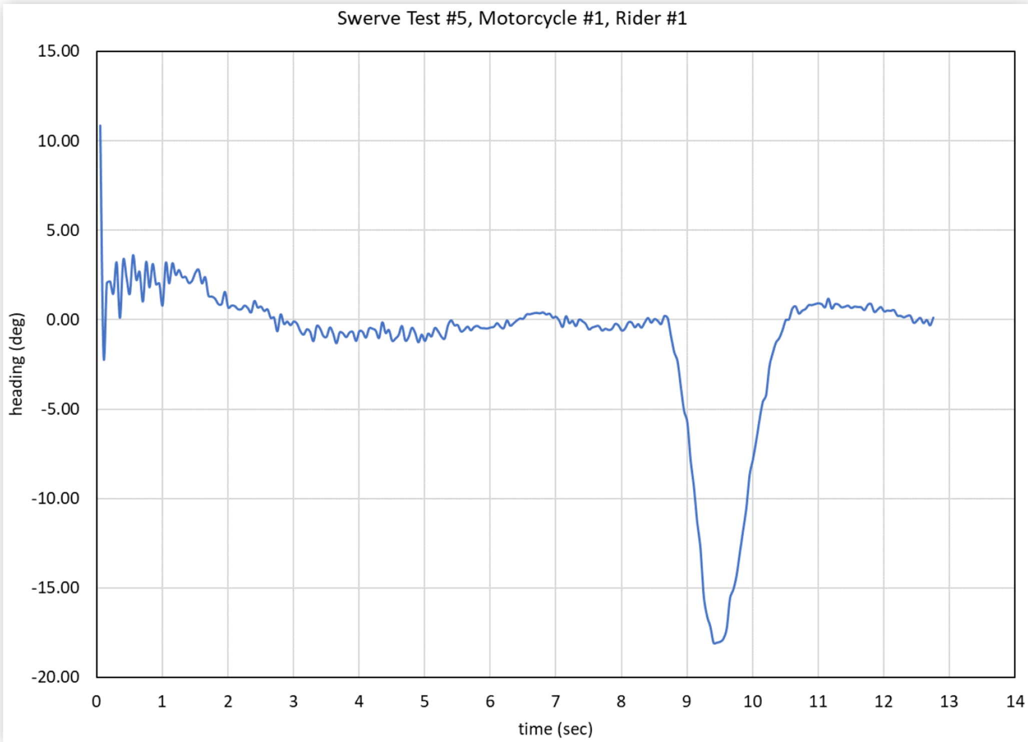


FIGURE B16 Speed, Swerve Test #6

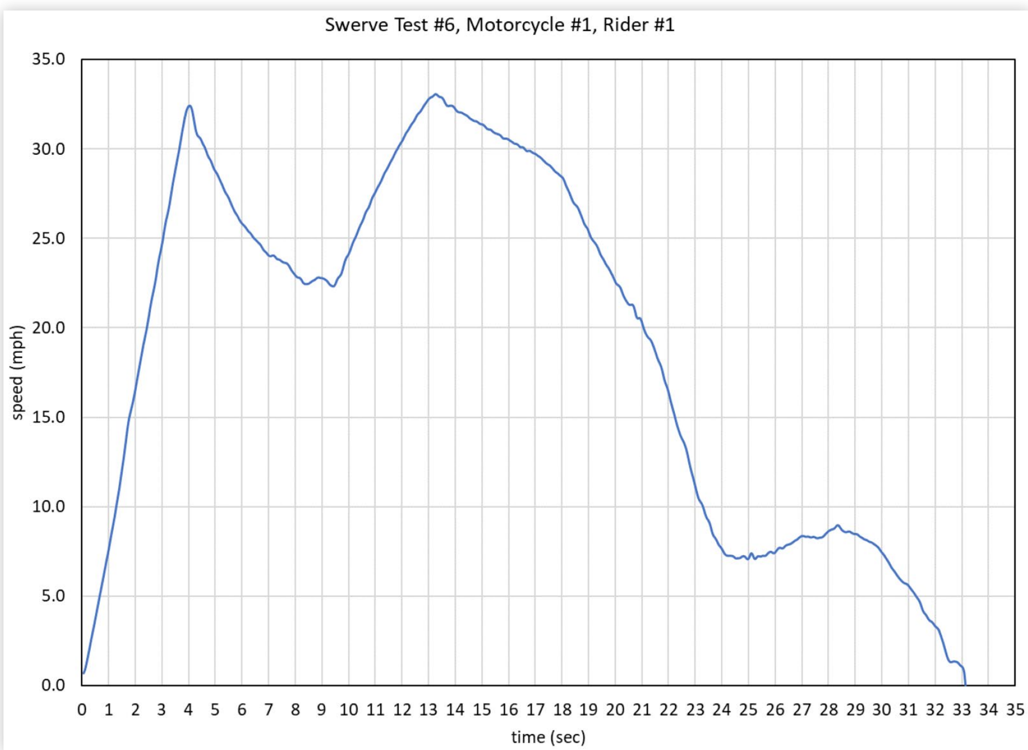


FIGURE B17 Lateral Acceleration, Swerve Test #6

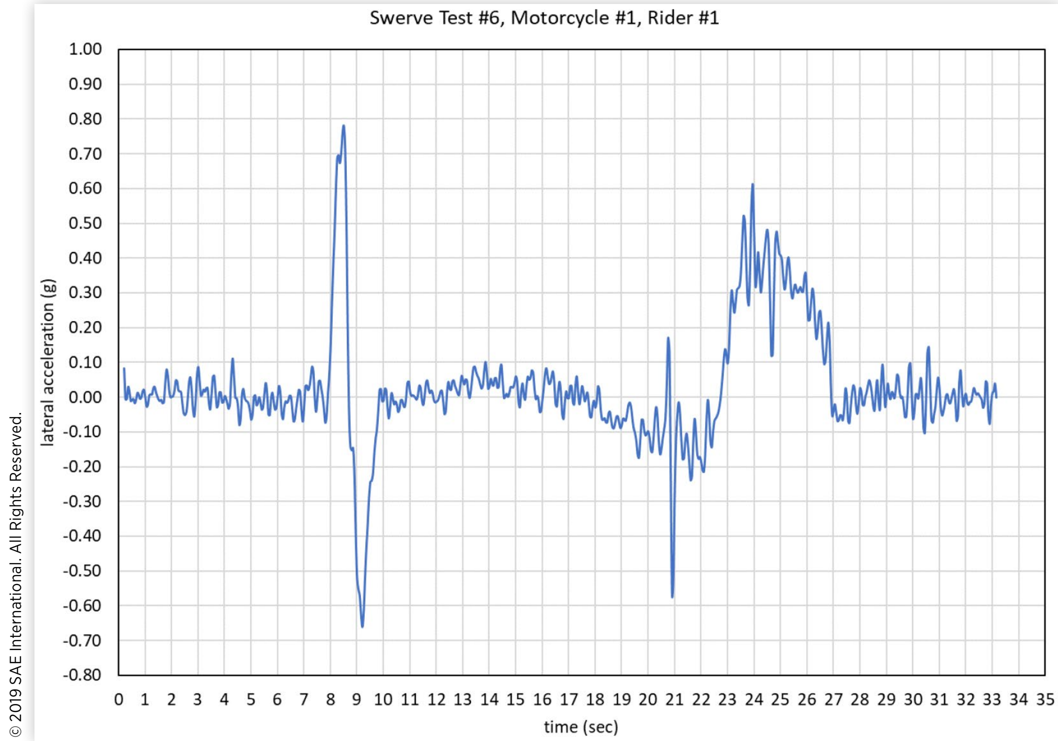


FIGURE B18 Heading, Swerve Test #6

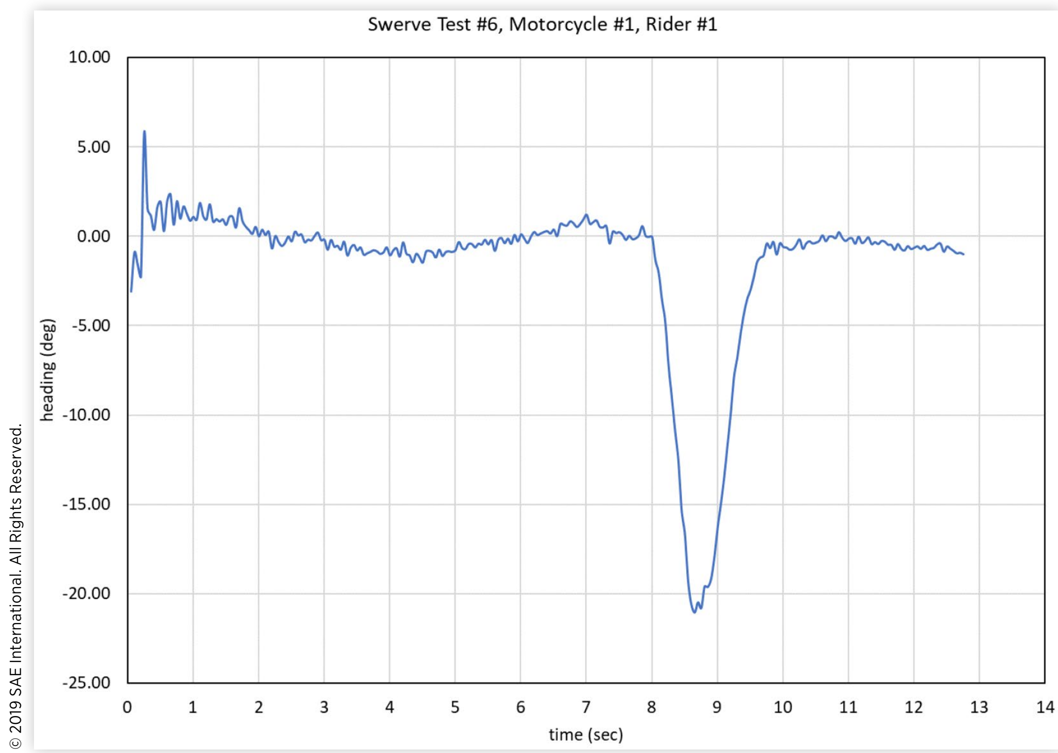


FIGURE B19 Speed, Swerve Test #7

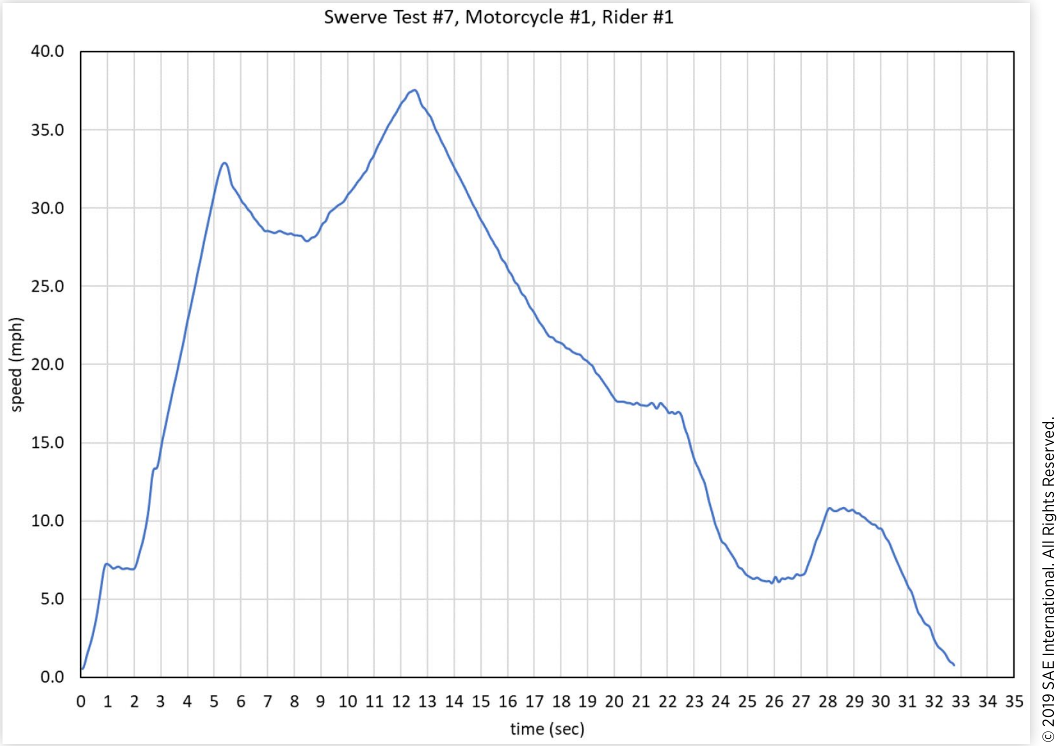


FIGURE B20 Lateral Acceleration, Swerve Test #7

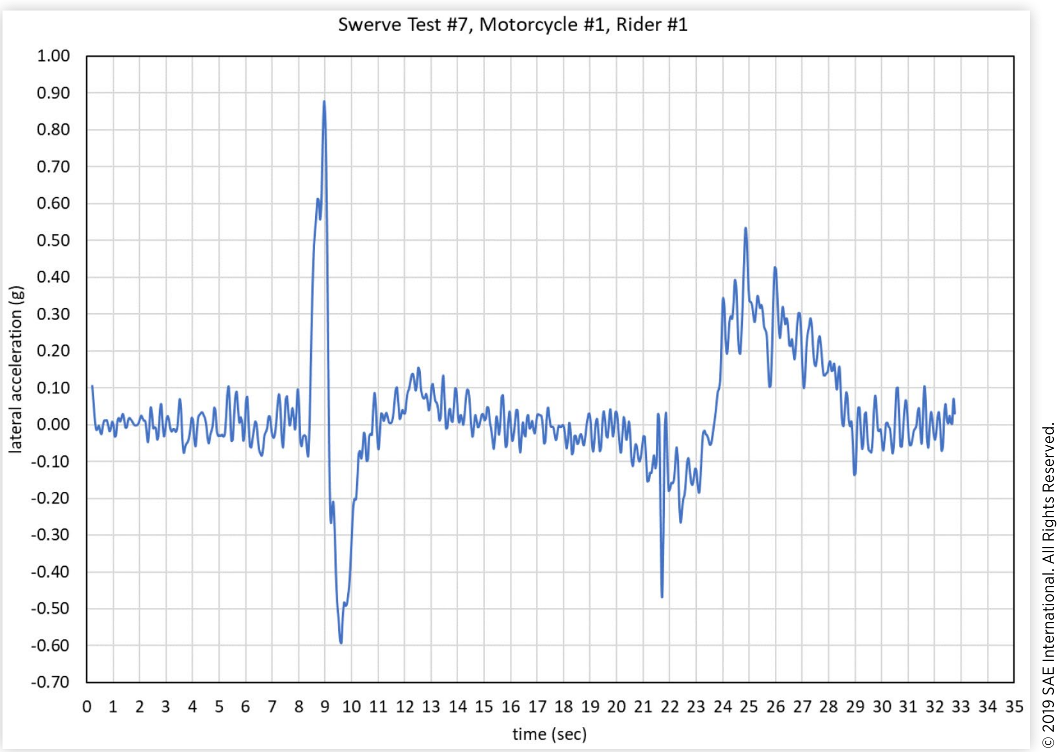


FIGURE B21 Heading, Swerve Test #7

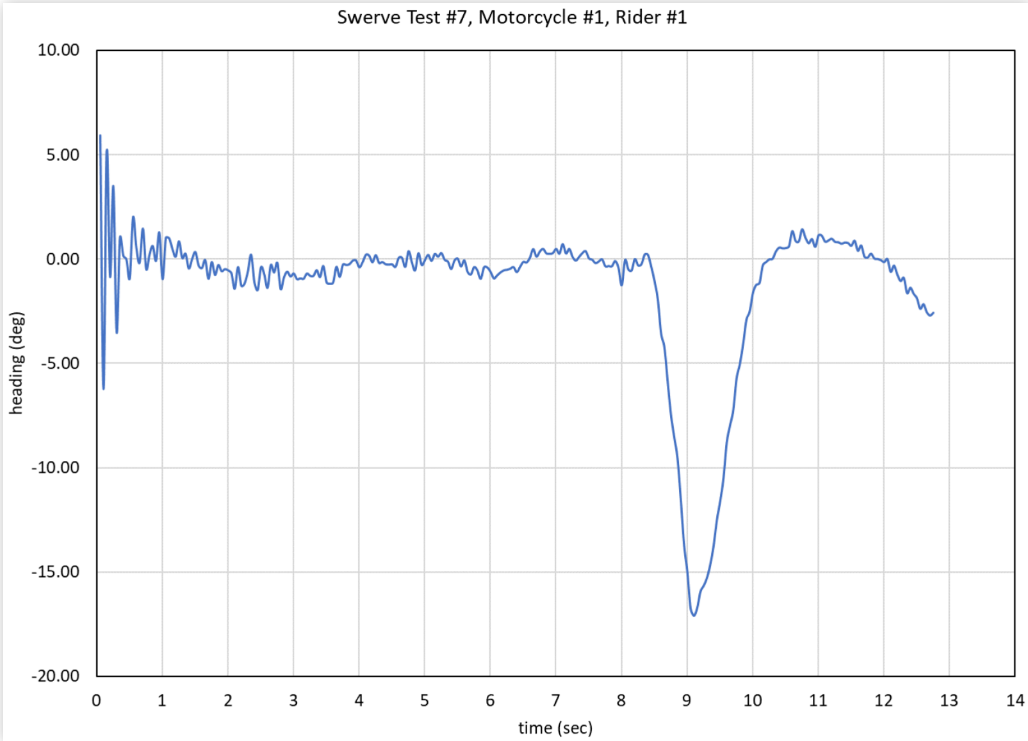


FIGURE B22 Speed, Swerve Test #8

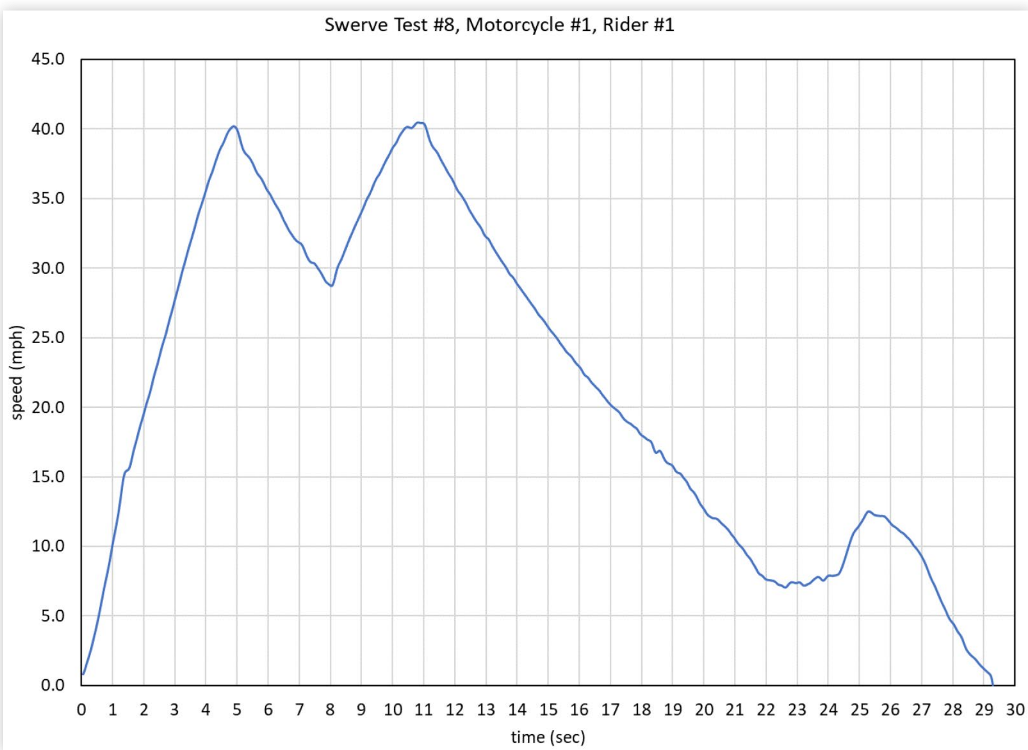


FIGURE B23 Lateral Acceleration, Swerve Test #8

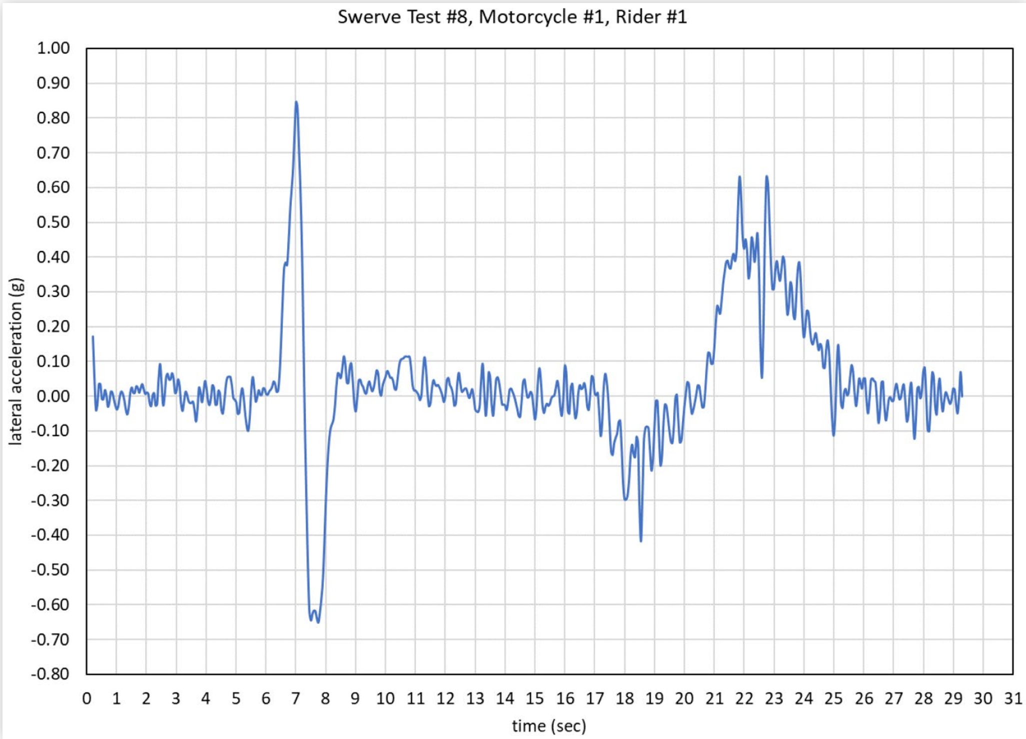


FIGURE B24 Heading, Swerve Test #8

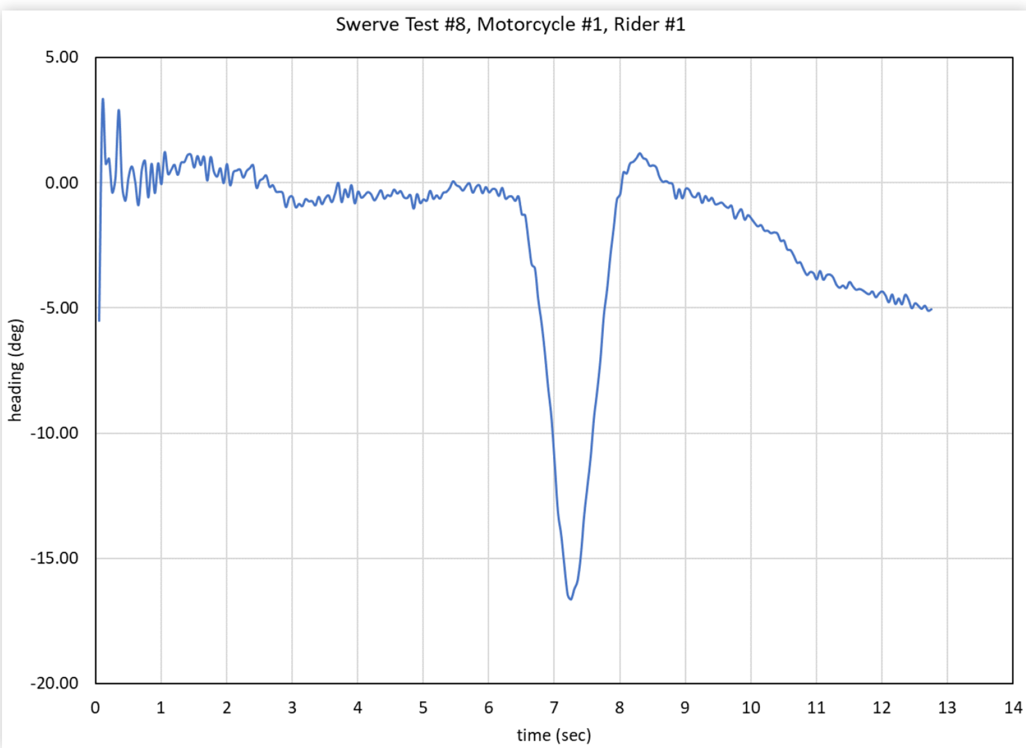


FIGURE B25 Speed, Swerve Test #9

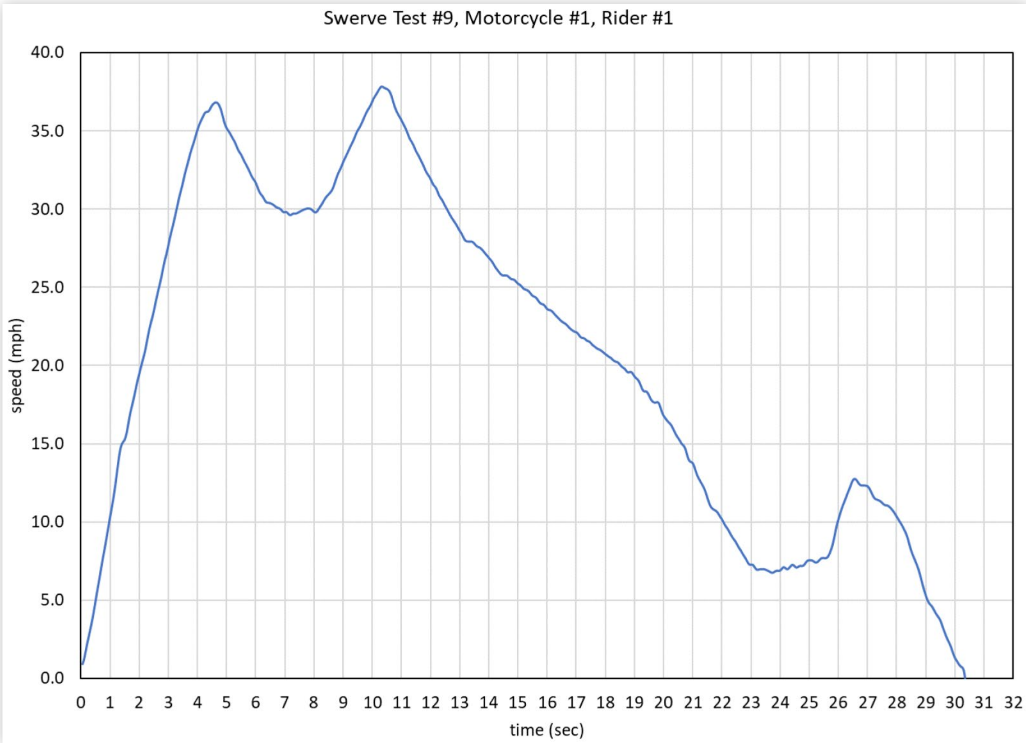


FIGURE B26 Lateral Acceleration, Swerve Test #9

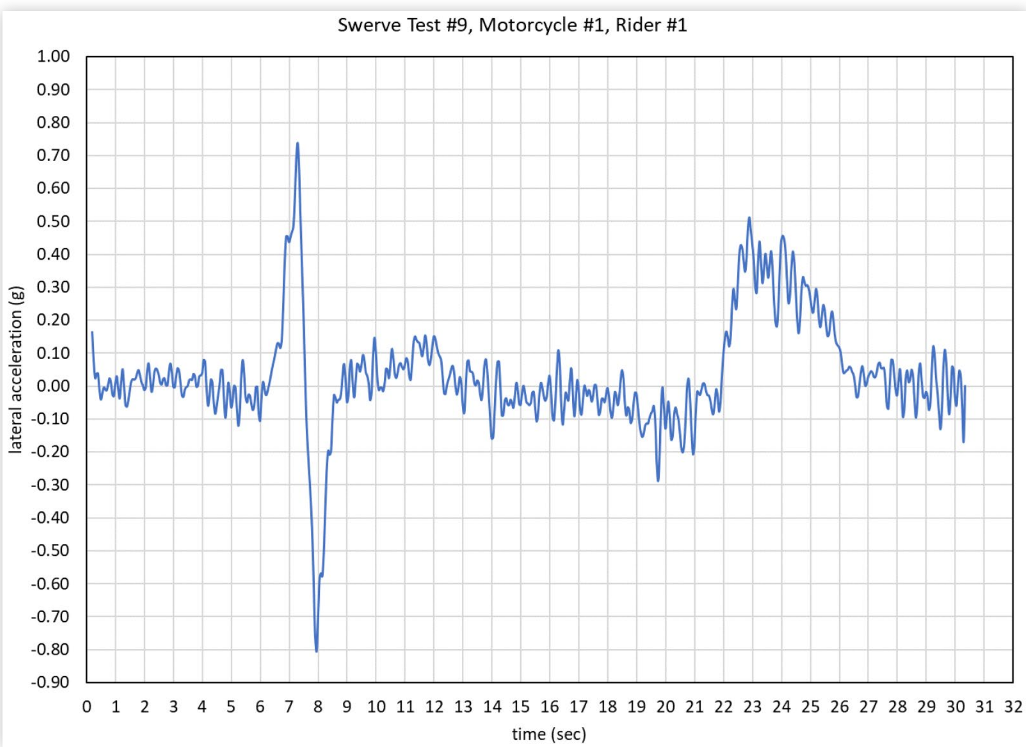


FIGURE B27 Heading, Swerve Test #9

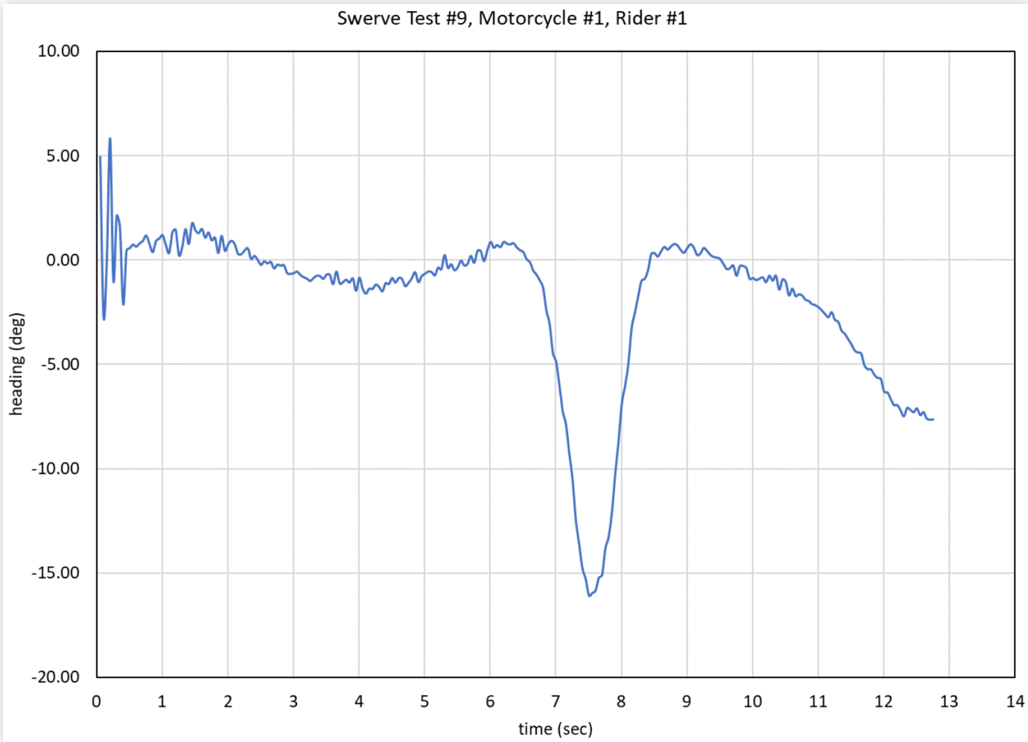


FIGURE B28 Speed, Swerve Test #10

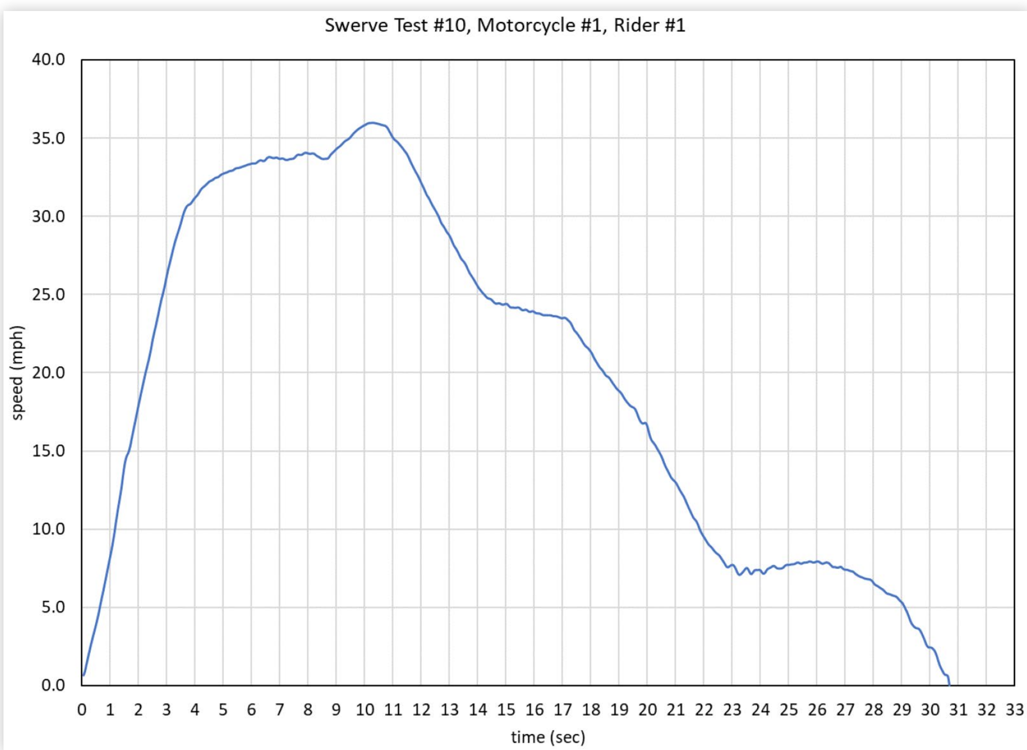


FIGURE B29 Lateral Acceleration, Swerve Test #10

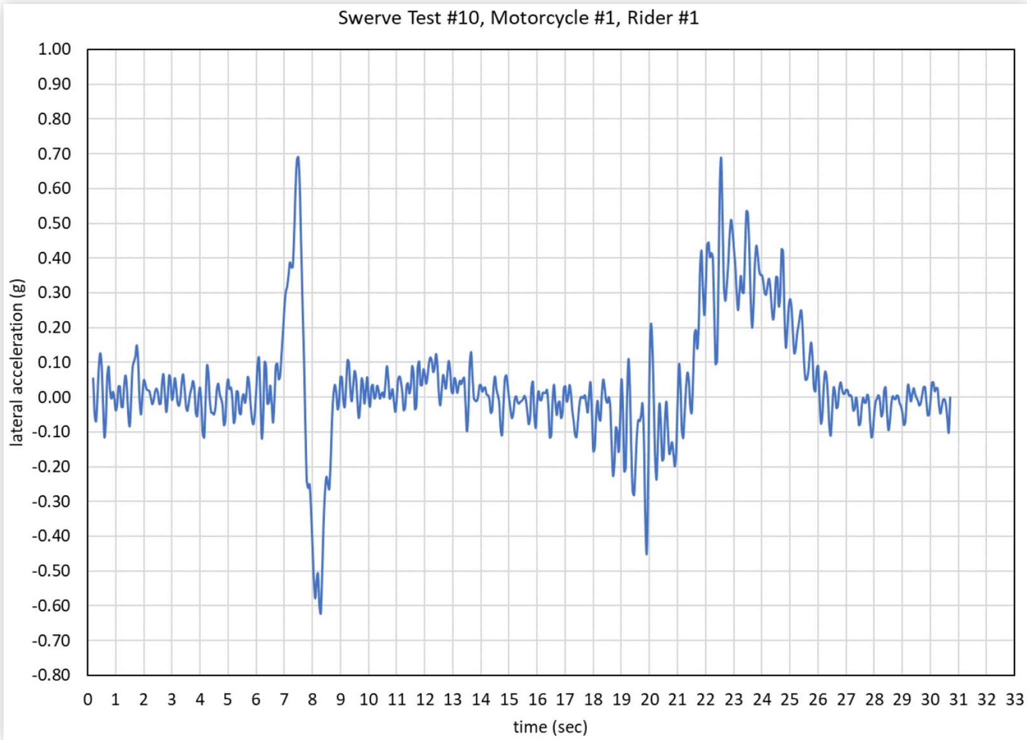


FIGURE B30 Heading, Swerve Test #10

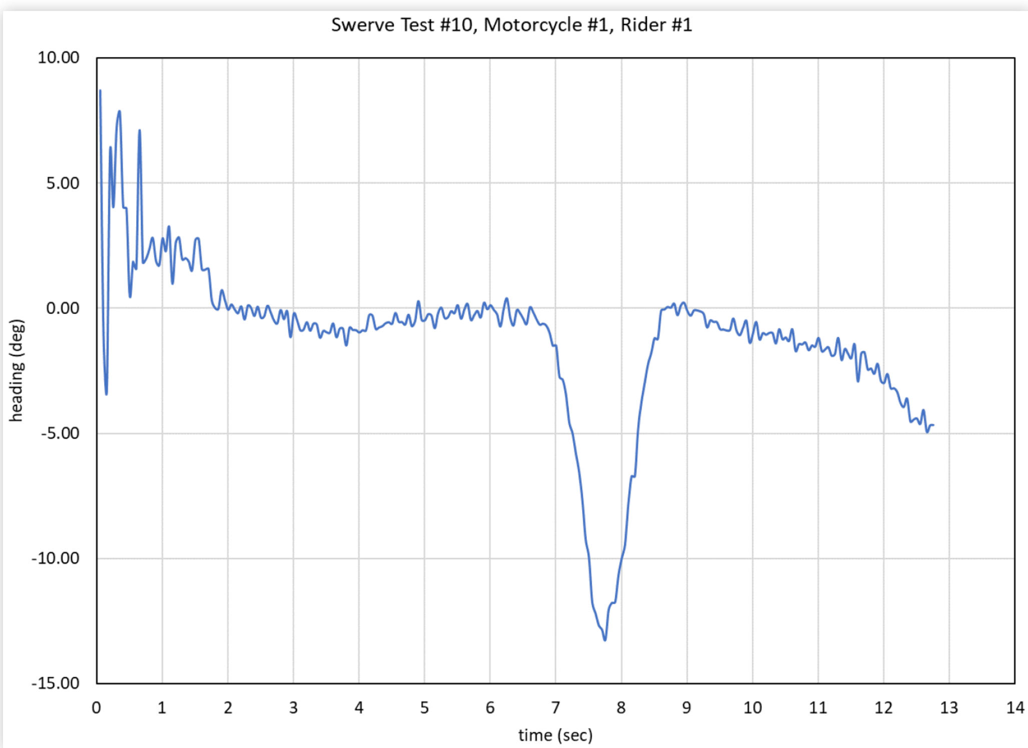


FIGURE B31 Speed, Swerve Test #11

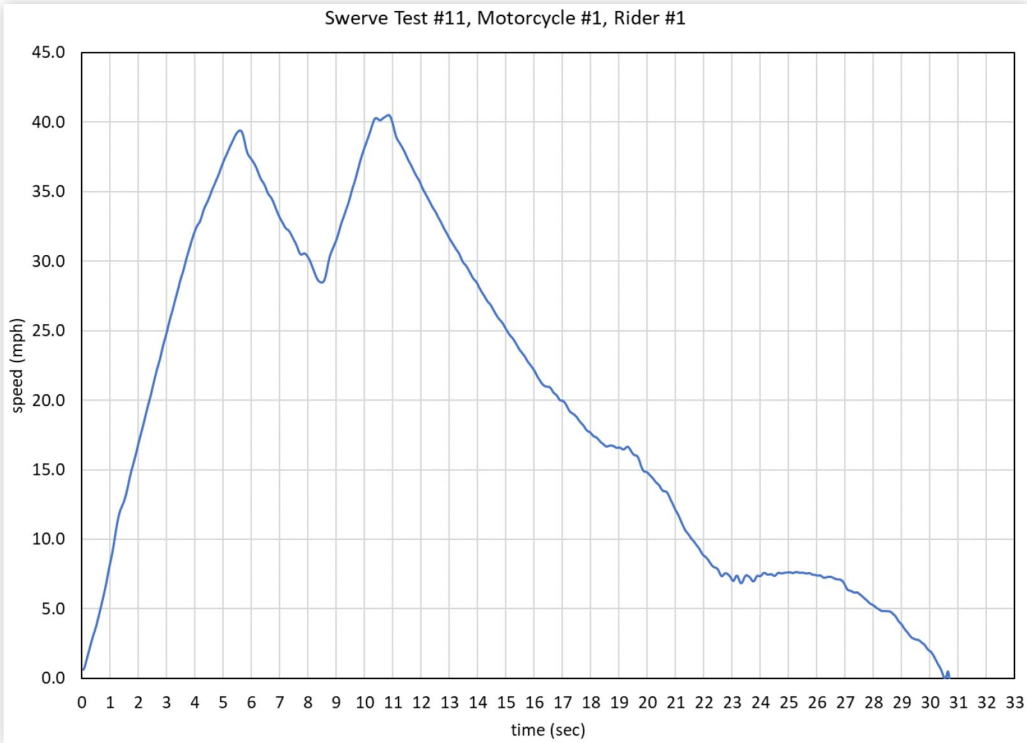


FIGURE B32 Lateral Acceleration, Swerve Test #11

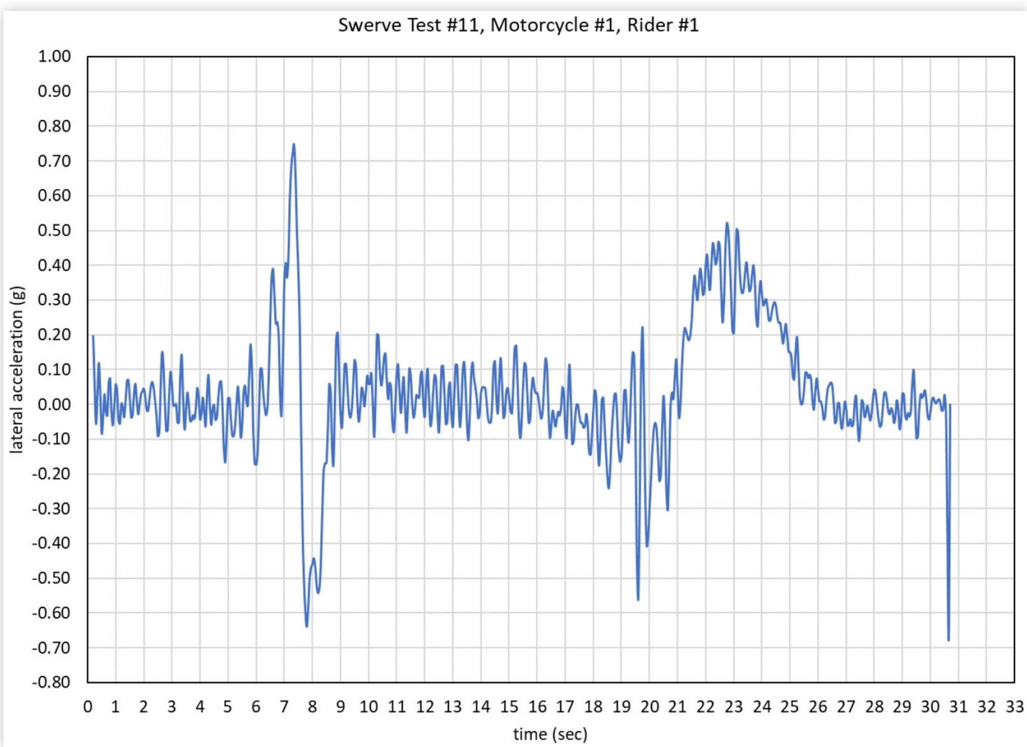


FIGURE B33 Heading, Swerve Test #11

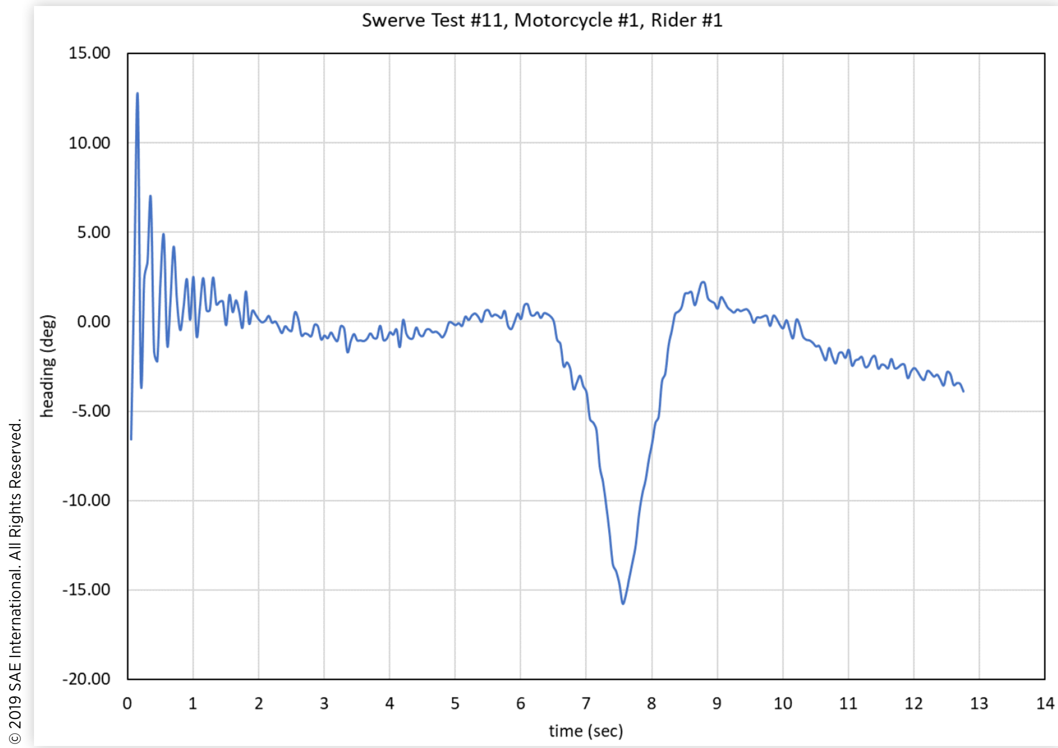


FIGURE B34 Speed, Swerve Test #12

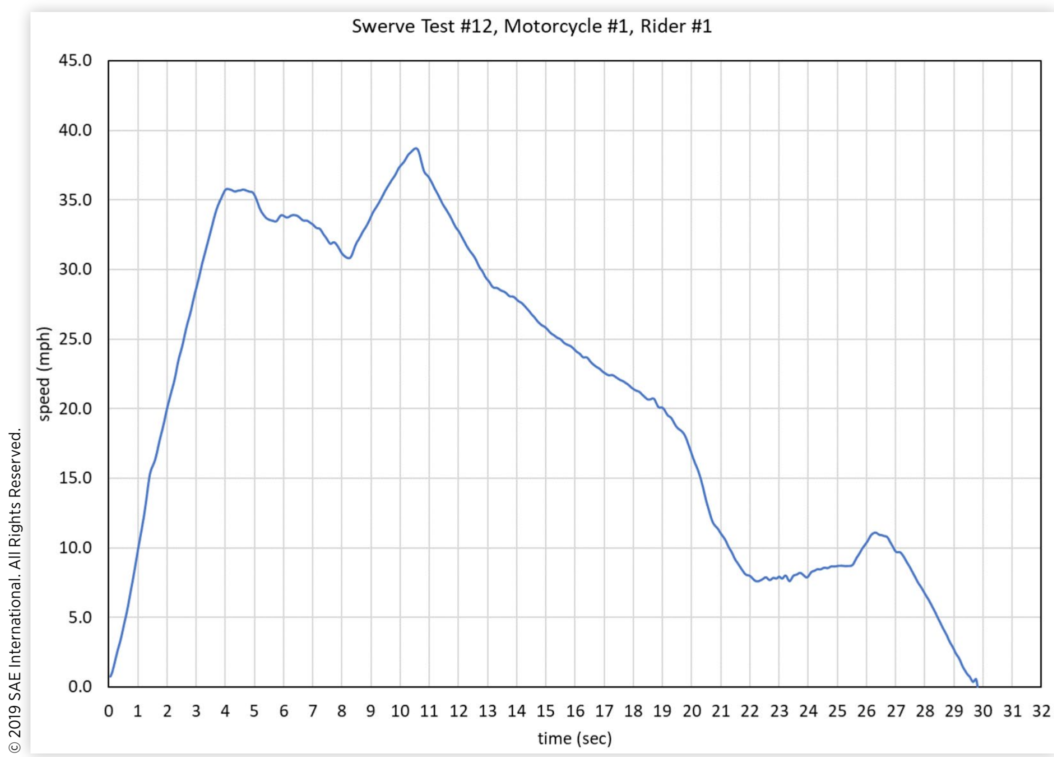


FIGURE B35 Lateral Acceleration, Swerve Test #12

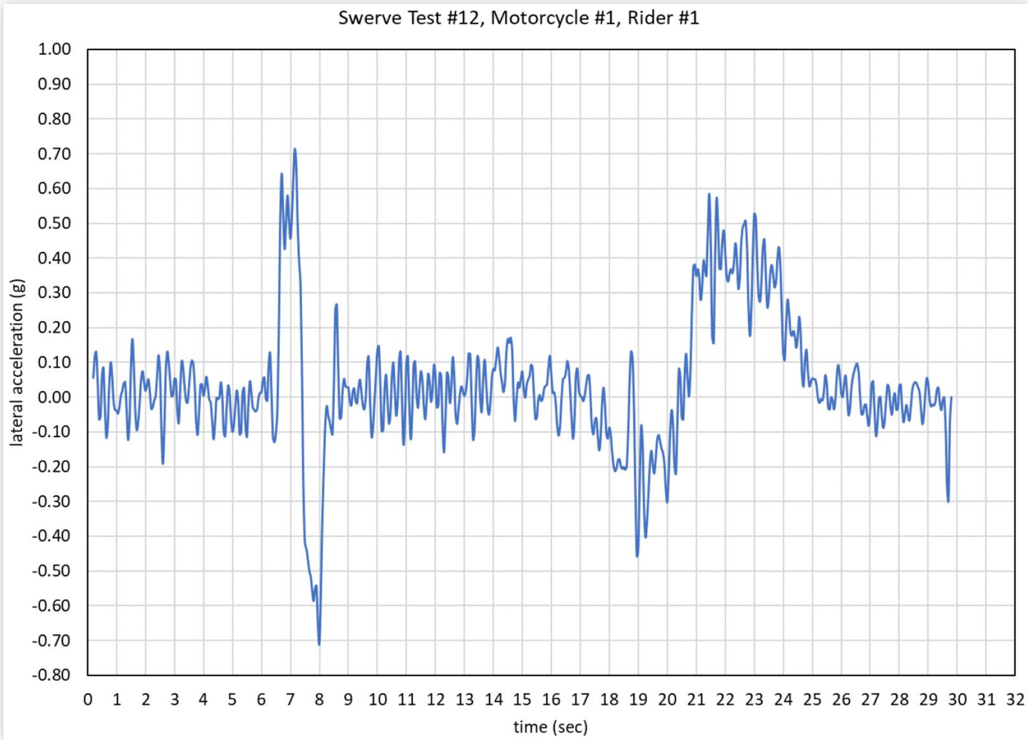


FIGURE B36 Heading, Swerve Test #12

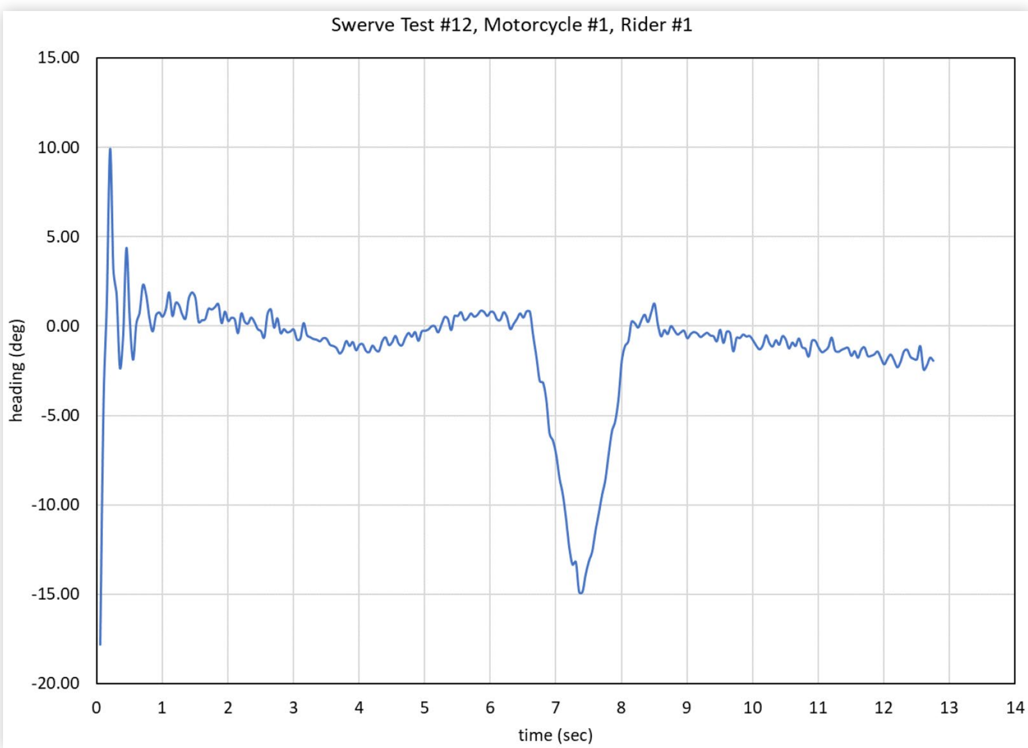


FIGURE B37 Speed, Swerve Test #13

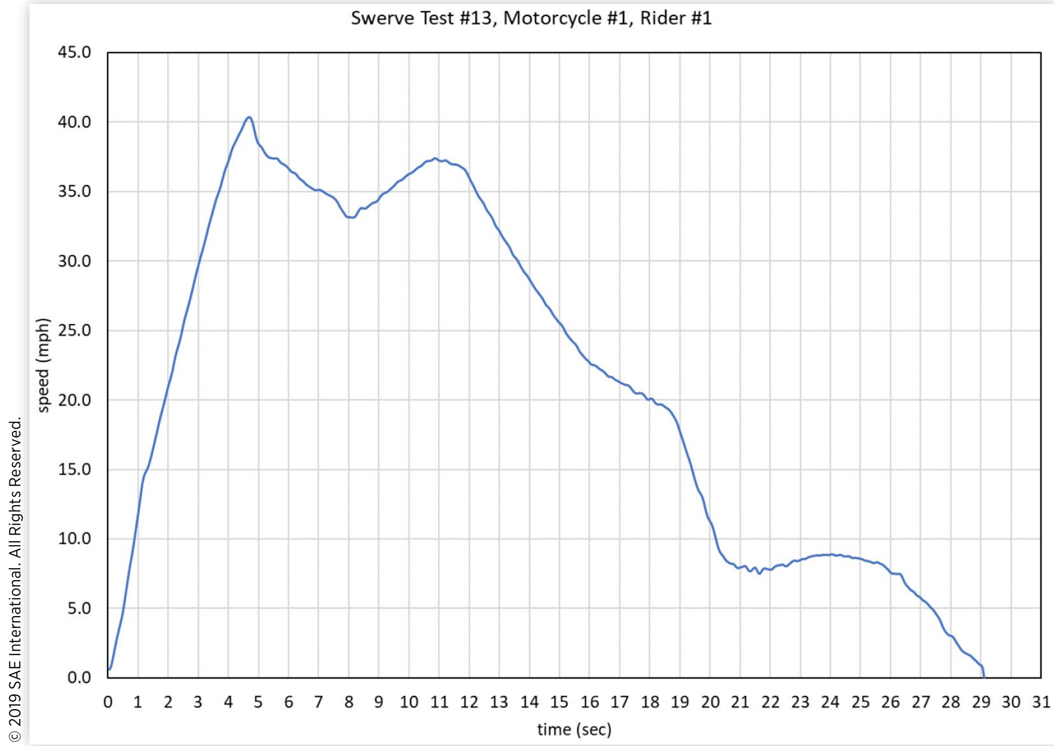


FIGURE B38 Lateral Acceleration, Swerve Test #13

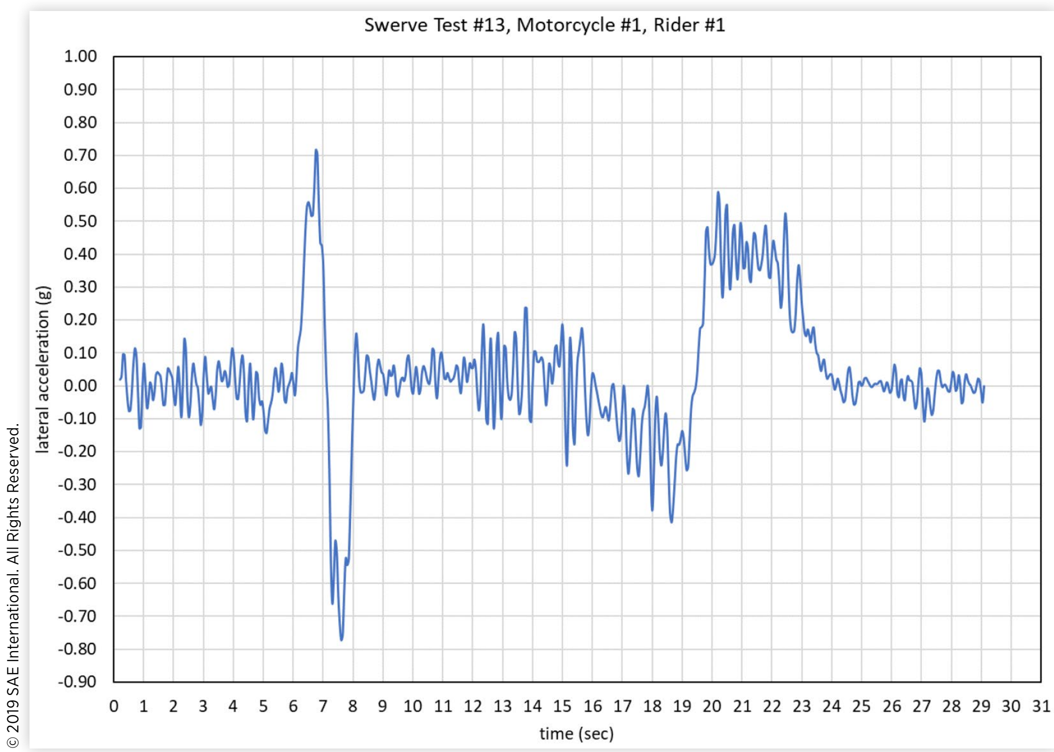


FIGURE B39 Heading, Swerve Test #13

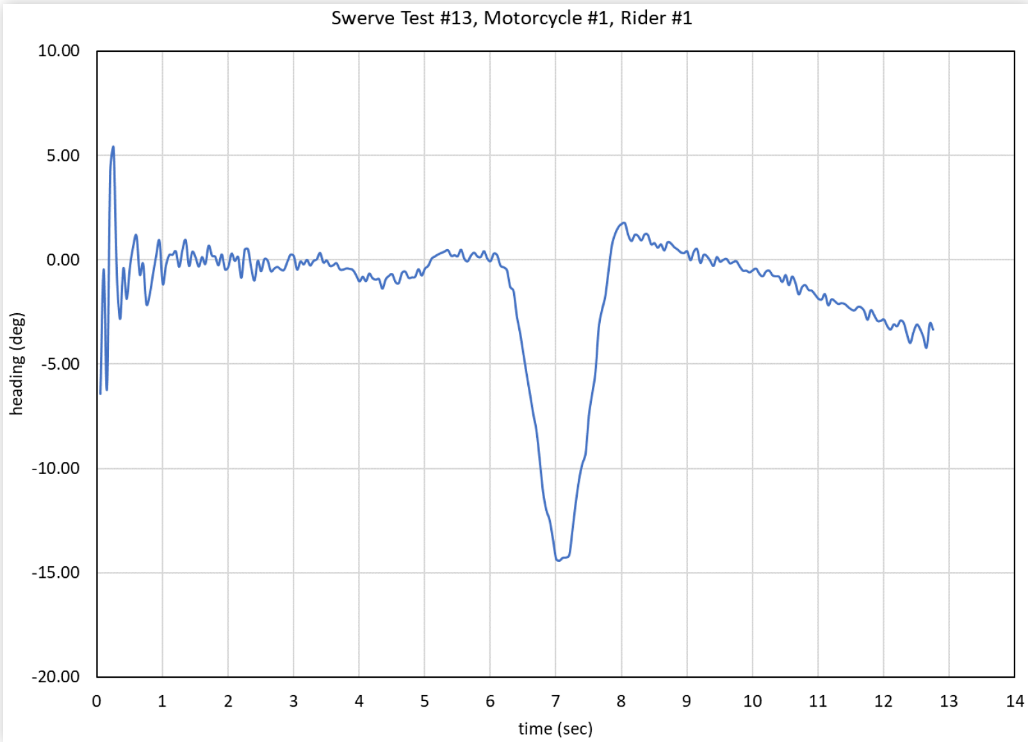


FIGURE B40 Speed, Swerve Test #14

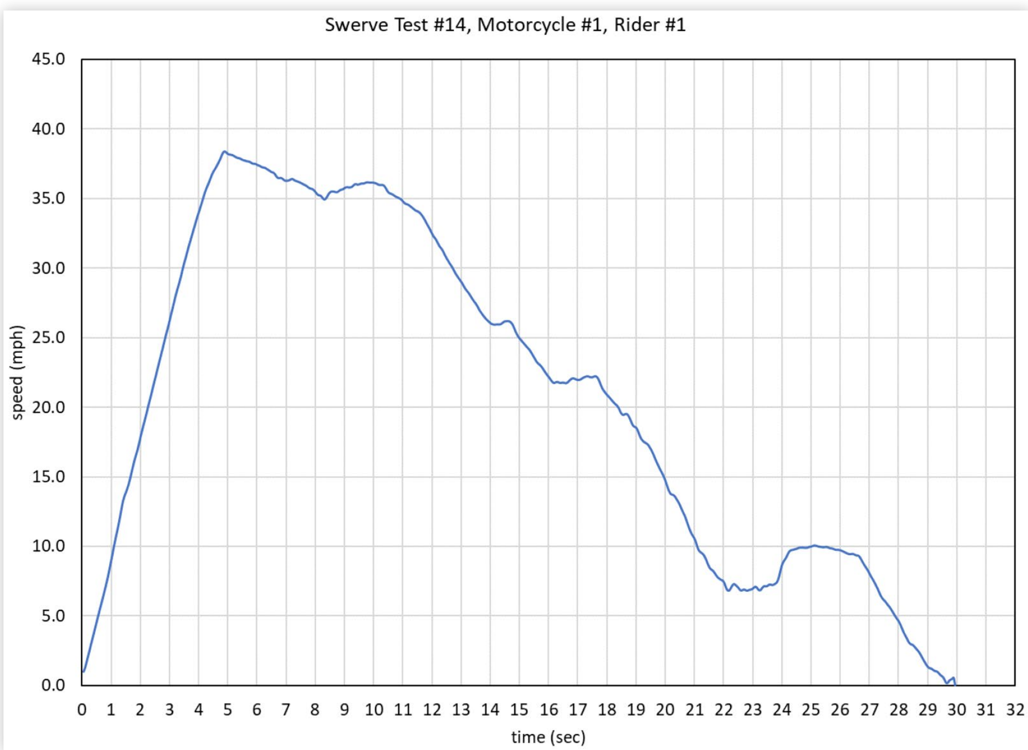


FIGURE B41 Lateral Acceleration, Swerve Test #14

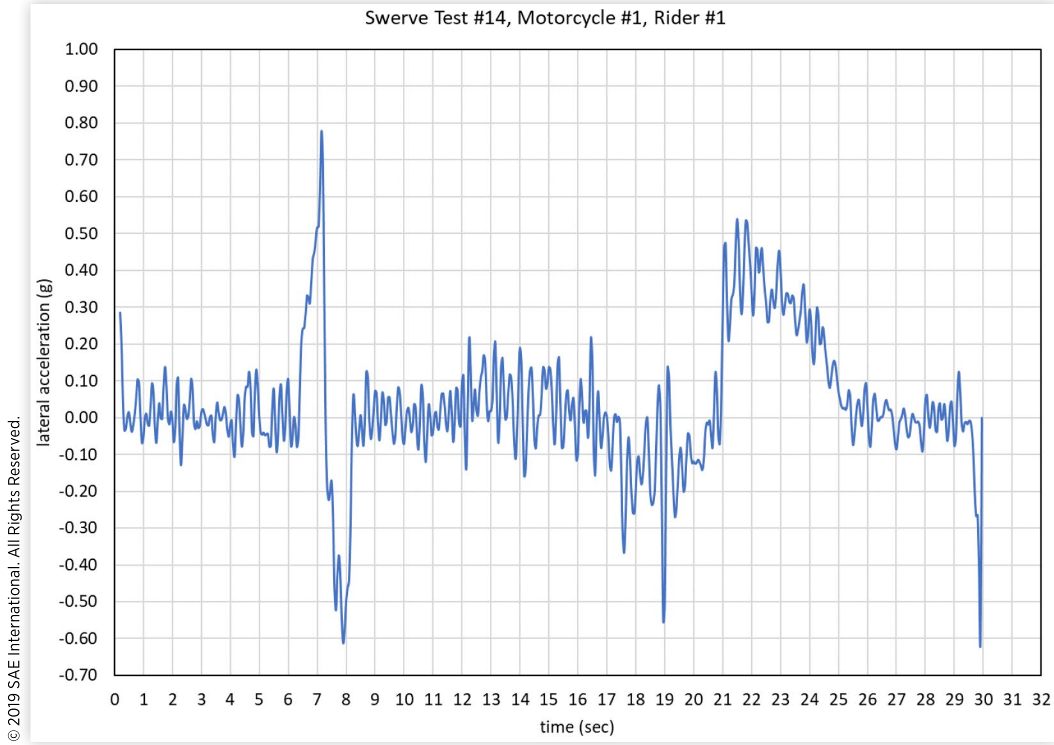


FIGURE B42 Heading, Swerve Test #14

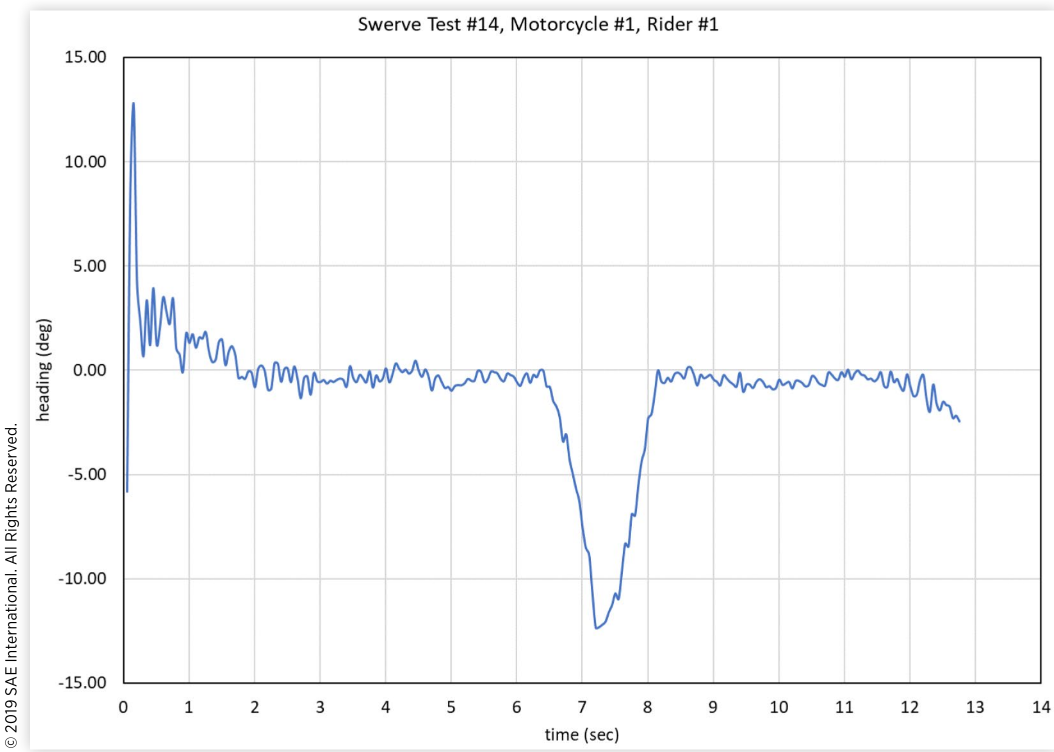


FIGURE B43 Speed, Swerve Test #15

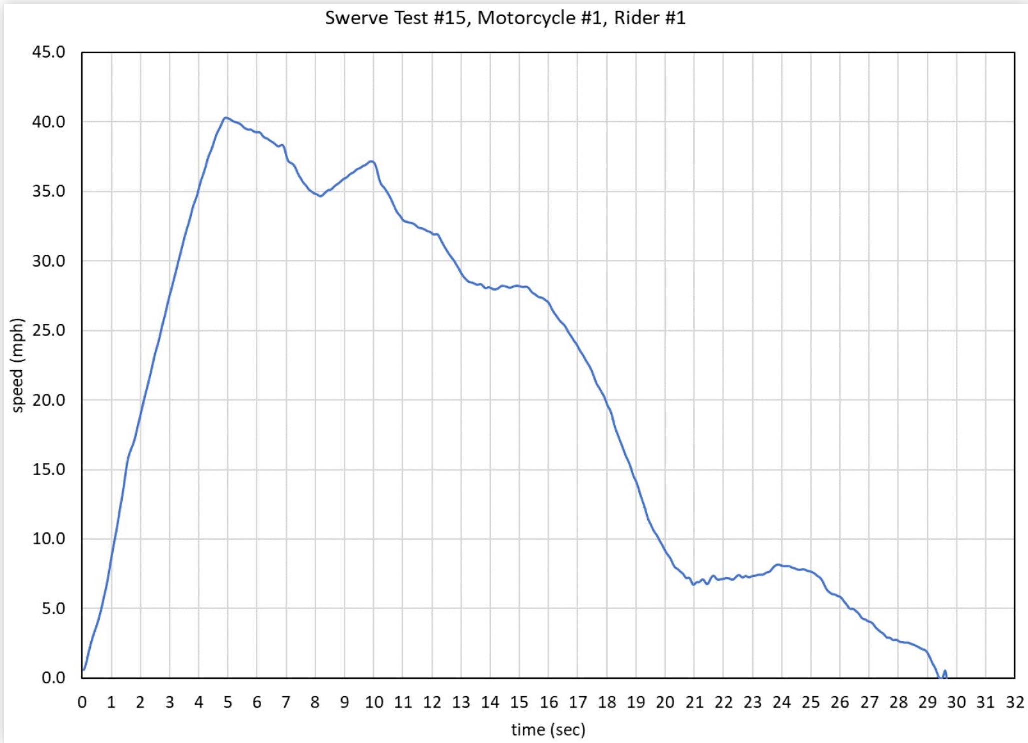


FIGURE B44 Lateral Acceleration, Swerve Test #15

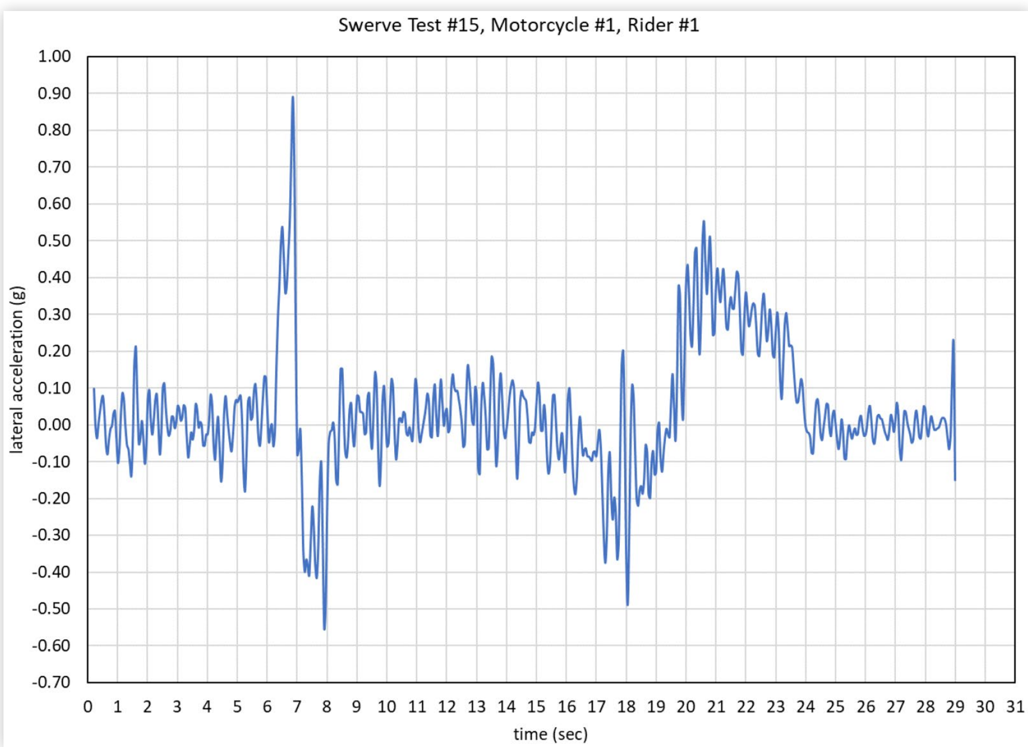


FIGURE B45 Heading, Swerve Test #15

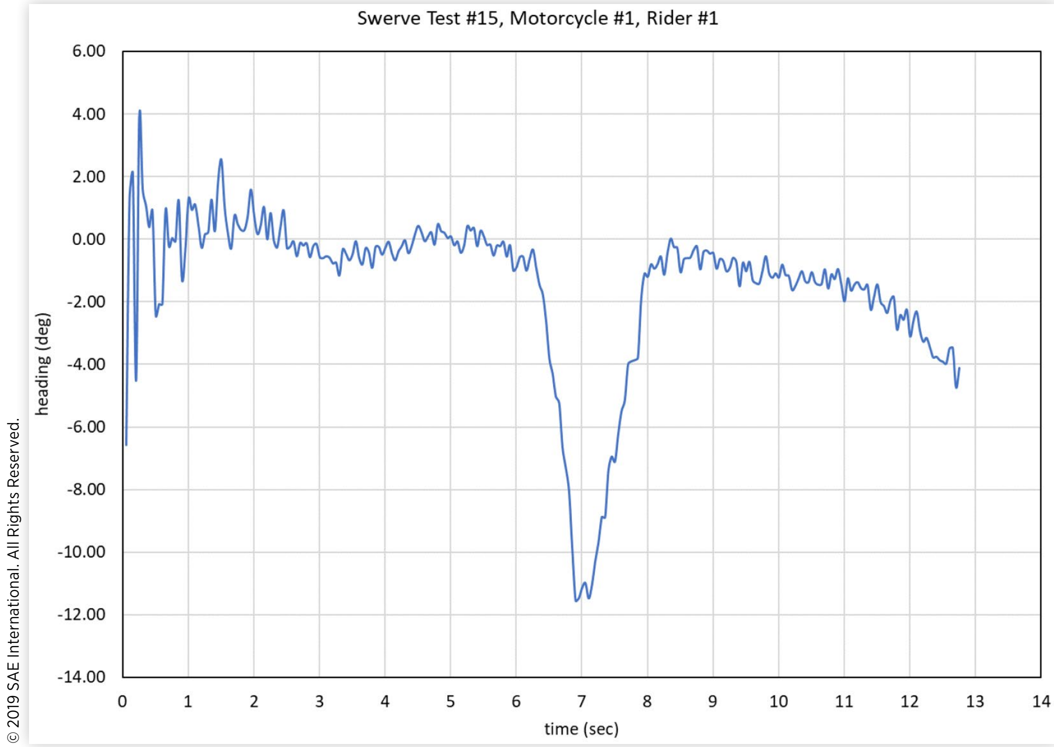


FIGURE B46 Speed, Swerve Test #16

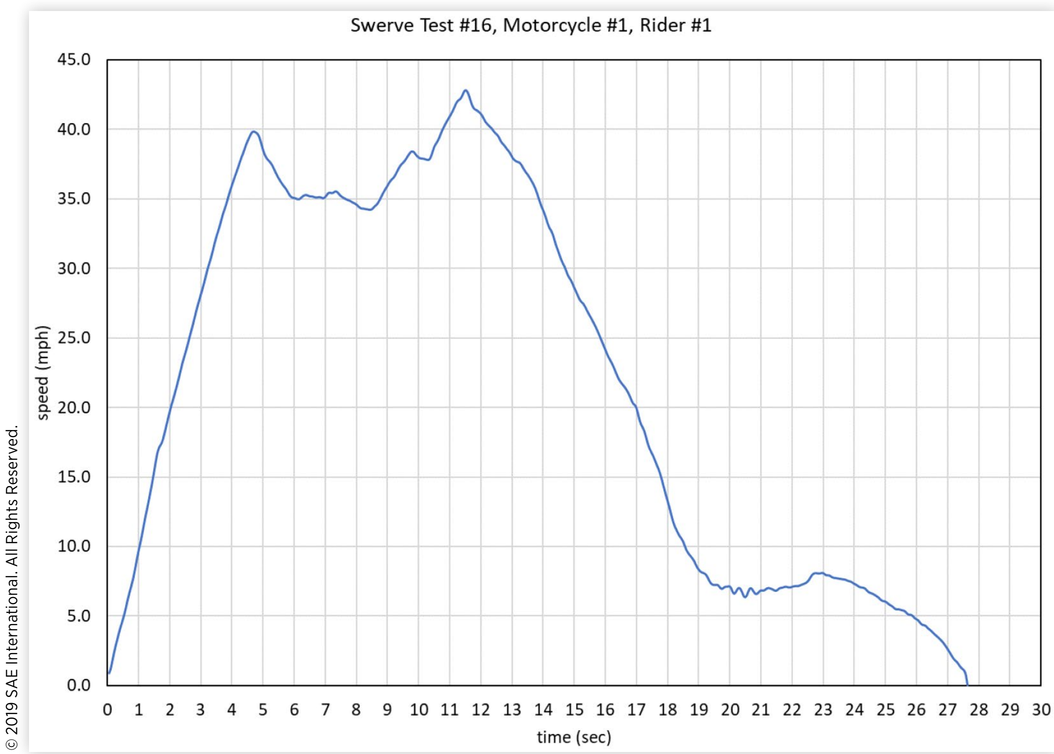


FIGURE B47 Lateral Acceleration, Swerve Test #16

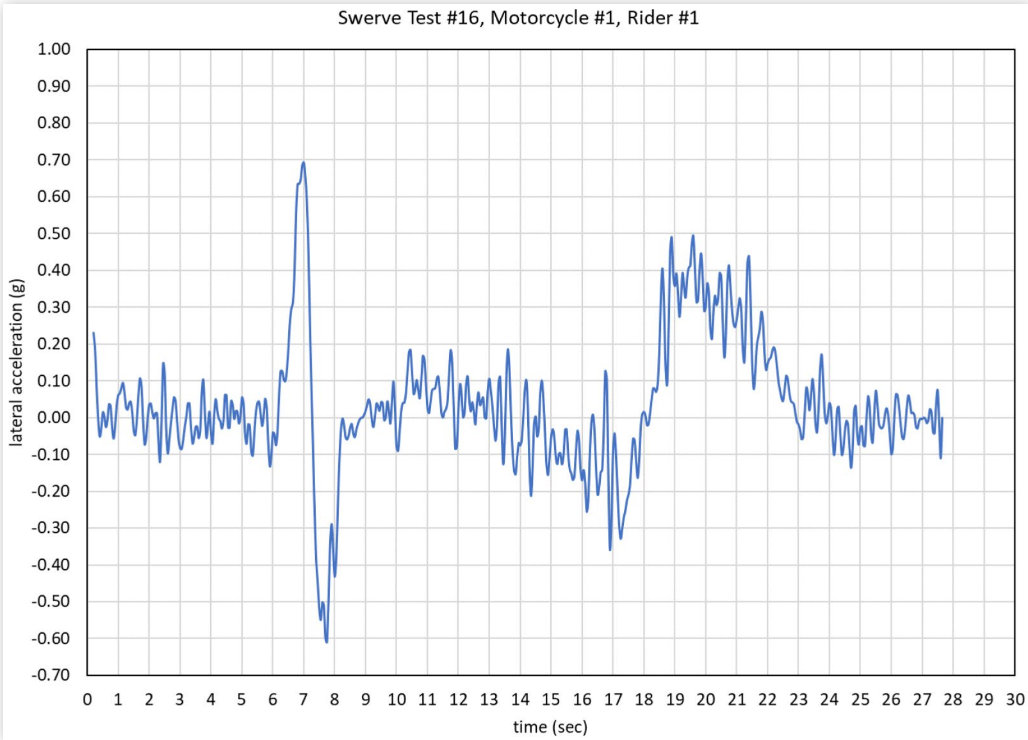


FIGURE B48 Heading, Swerve Test #16

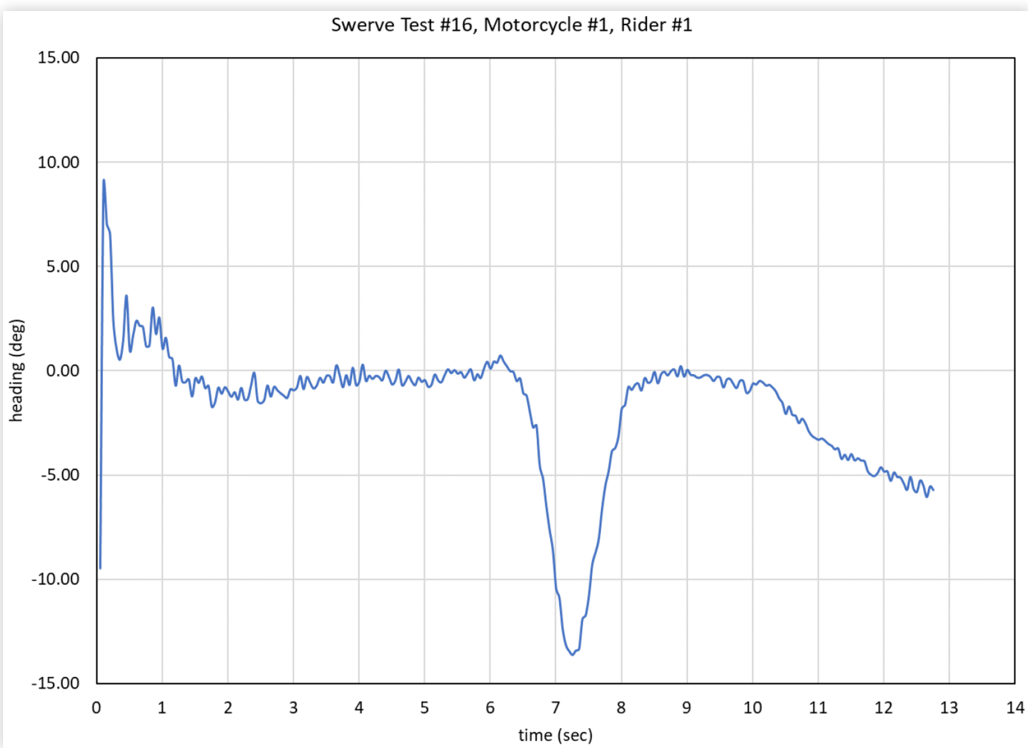


FIGURE B49 Speed, Swerve Test #17

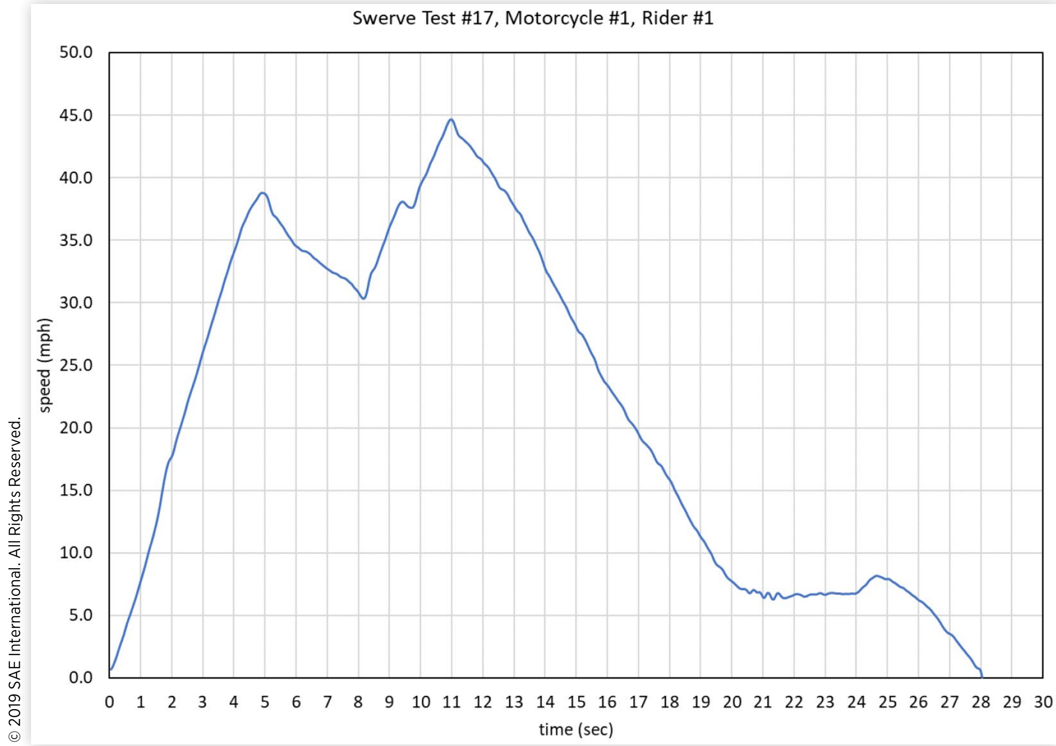


FIGURE B50 Lateral Acceleration, Swerve Test #17

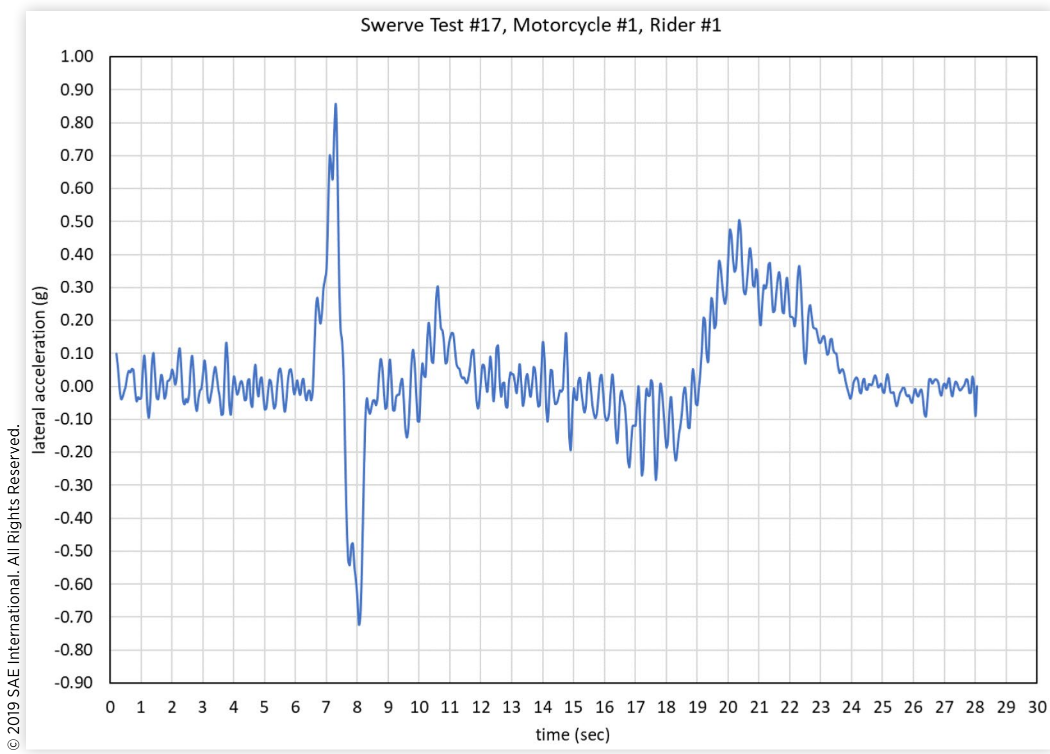


FIGURE B51 Heading, Swerve Test #17

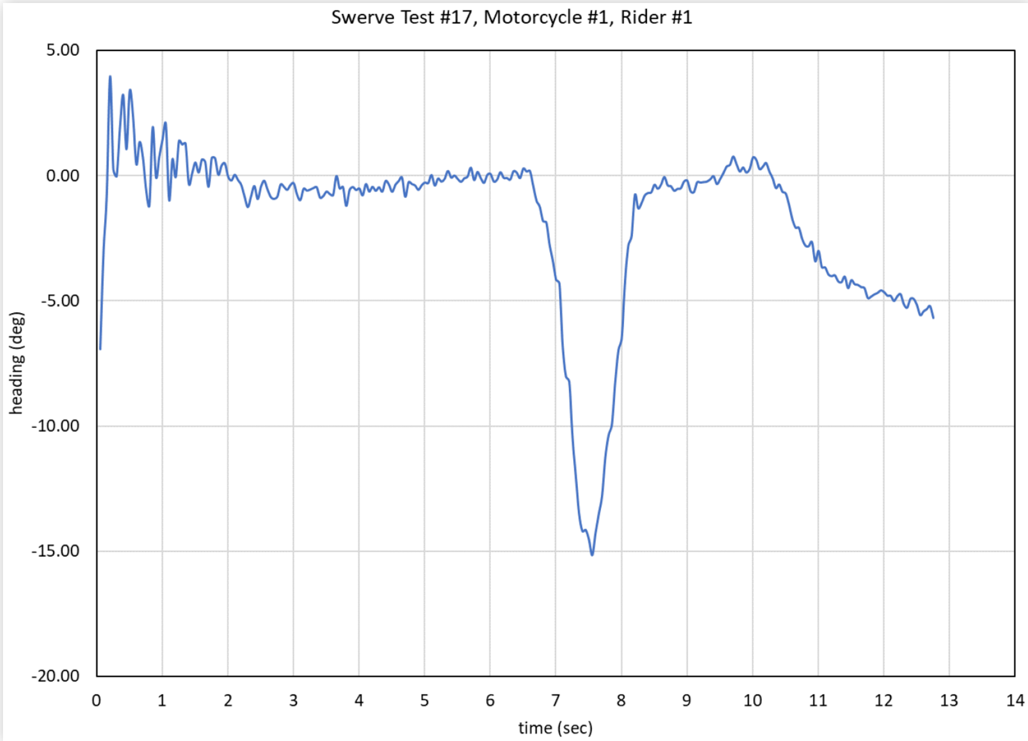


FIGURE B52 Speed, Swerve Test #18

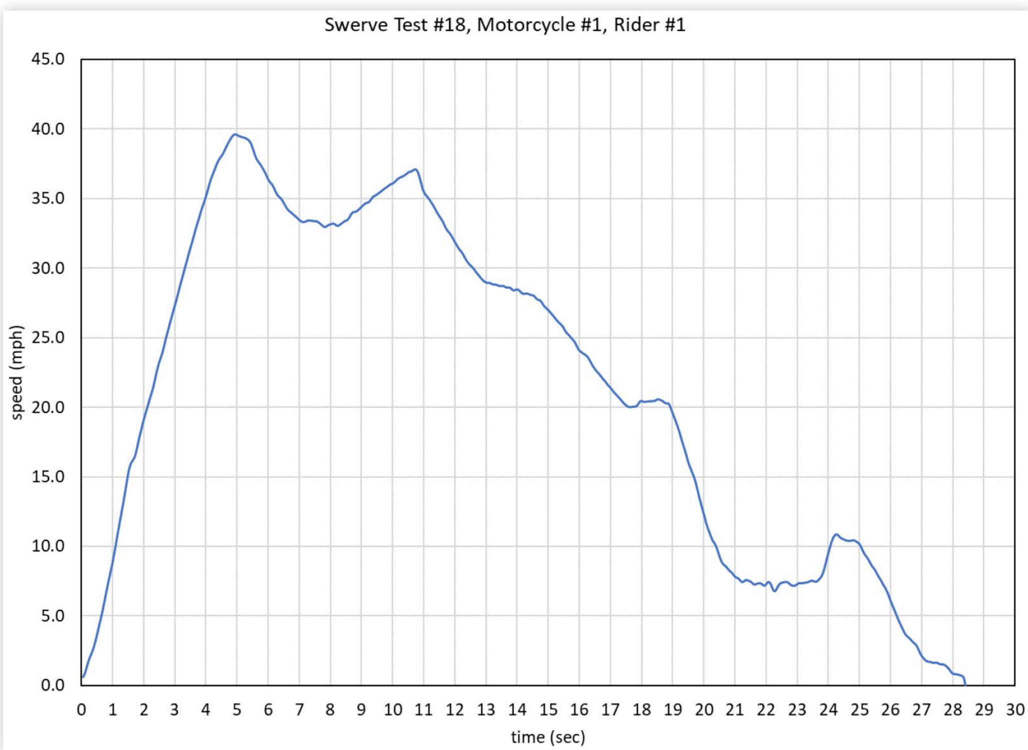


FIGURE B53 Lateral Acceleration, Swerve Test #18

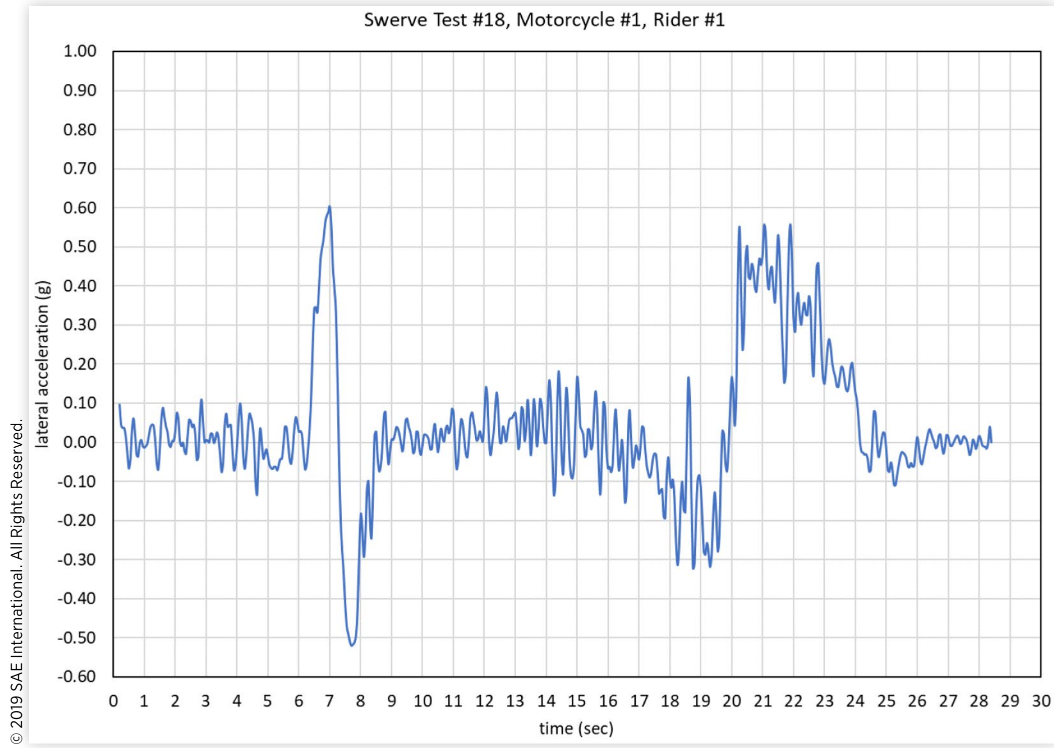


FIGURE B54 Heading, Swerve Test #18

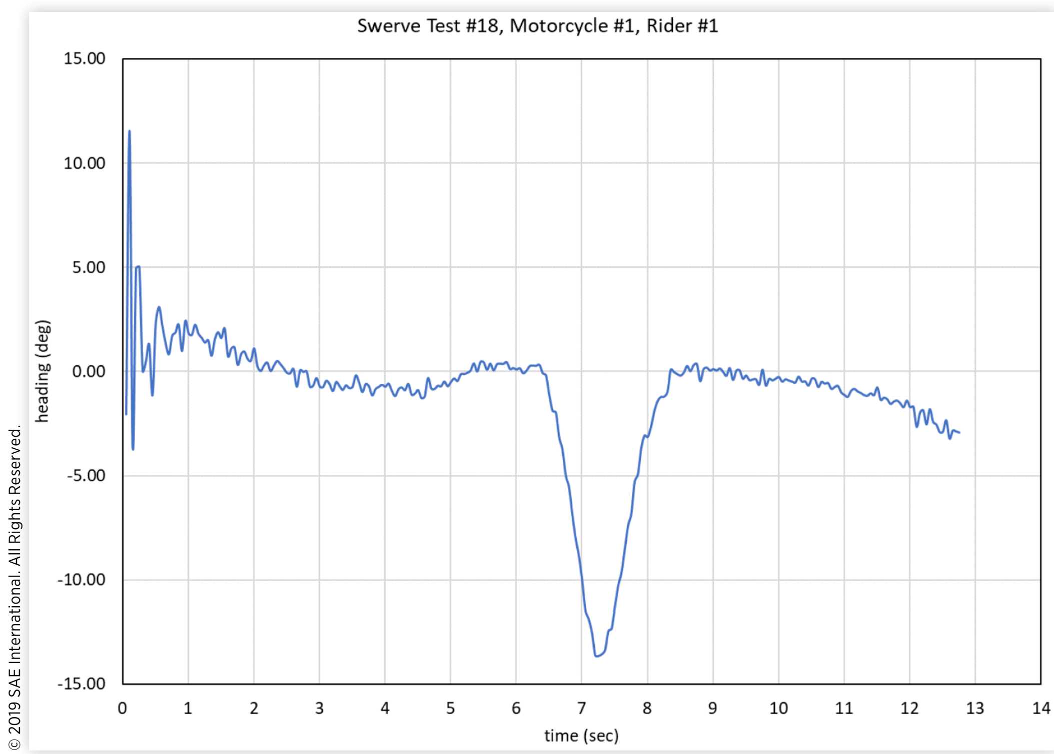


FIGURE B55 Speed, Swerve Test #19

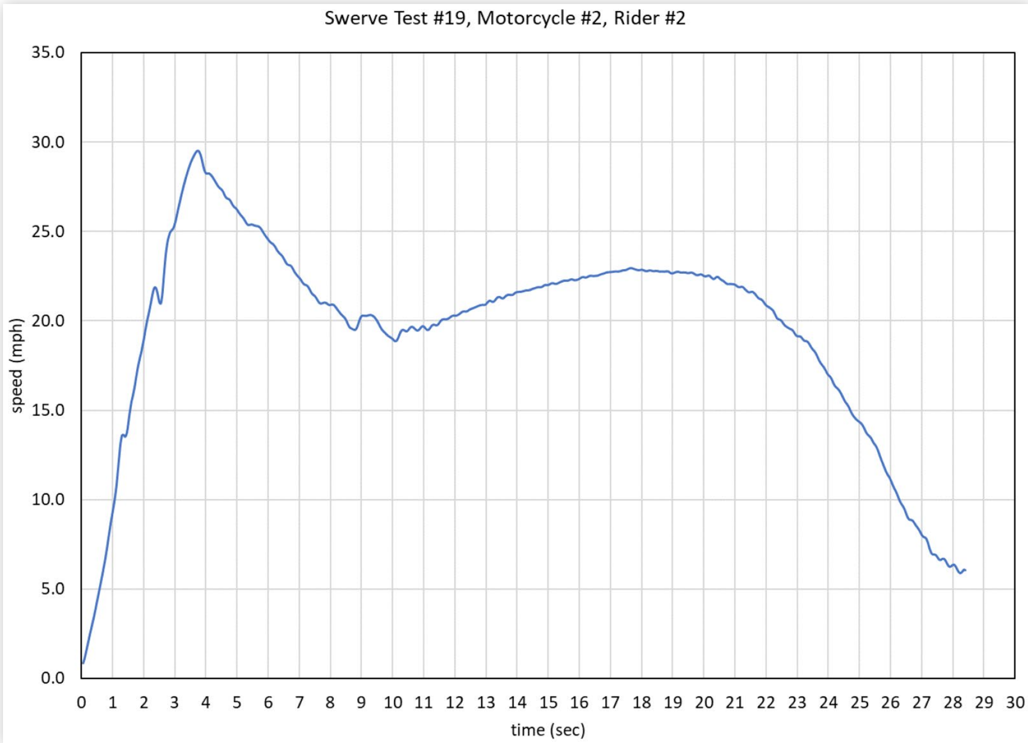


FIGURE B56 Lateral Acceleration, Swerve Test #19

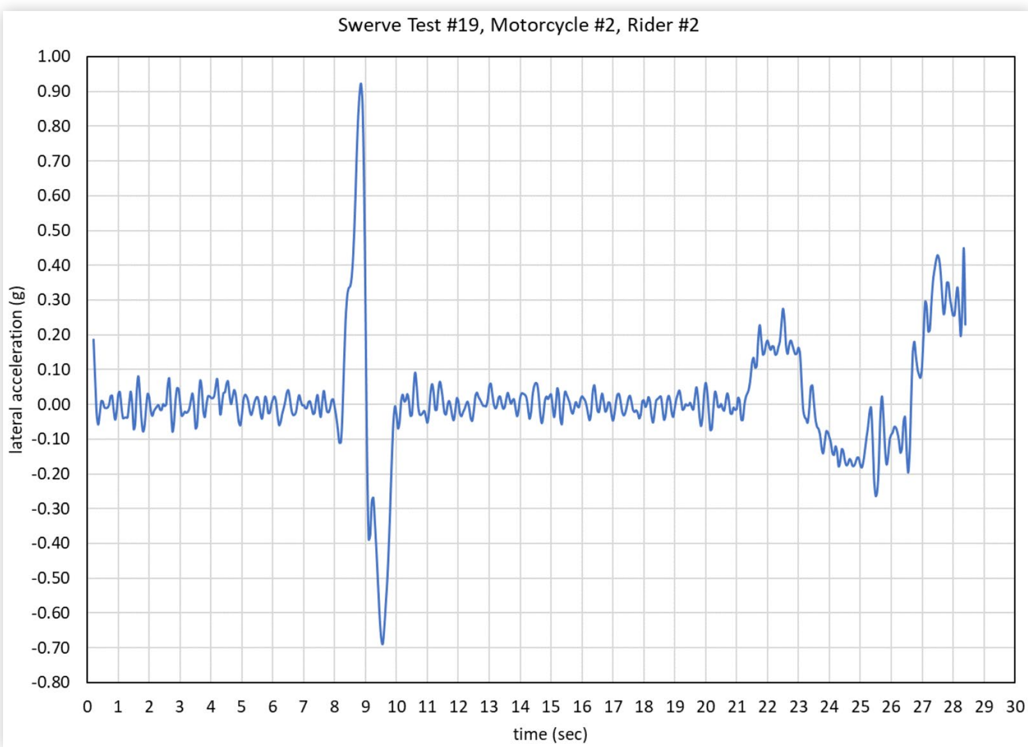


FIGURE B57 Heading, Swerve Test #19

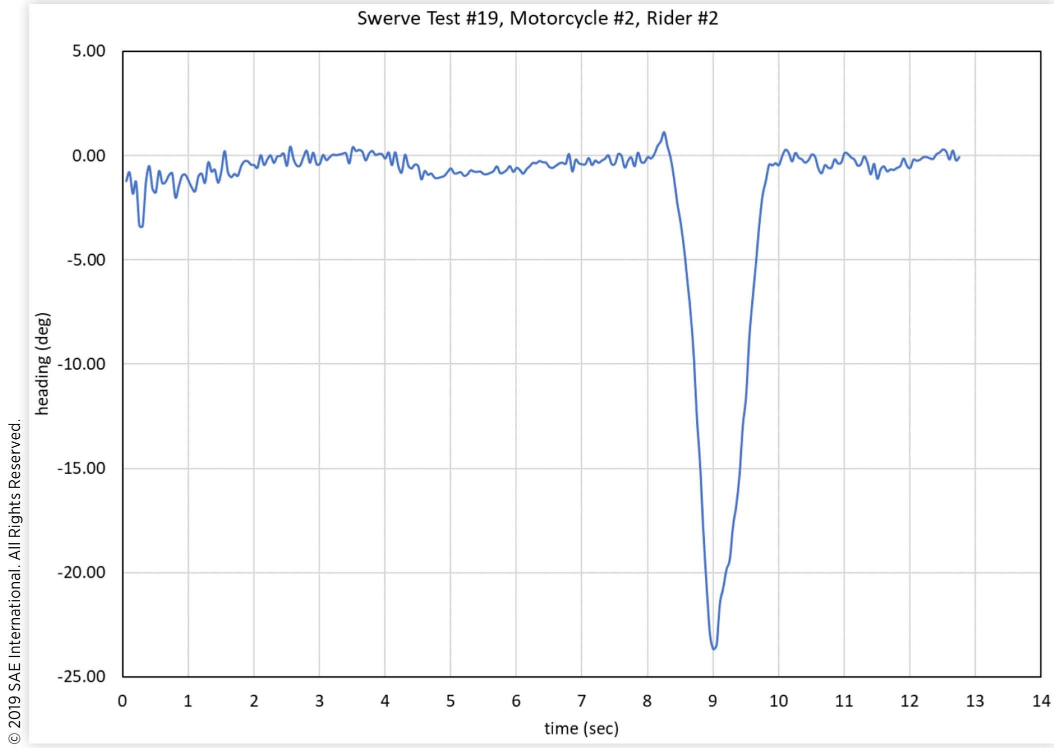


FIGURE B58 Speed, Swerve Test #20

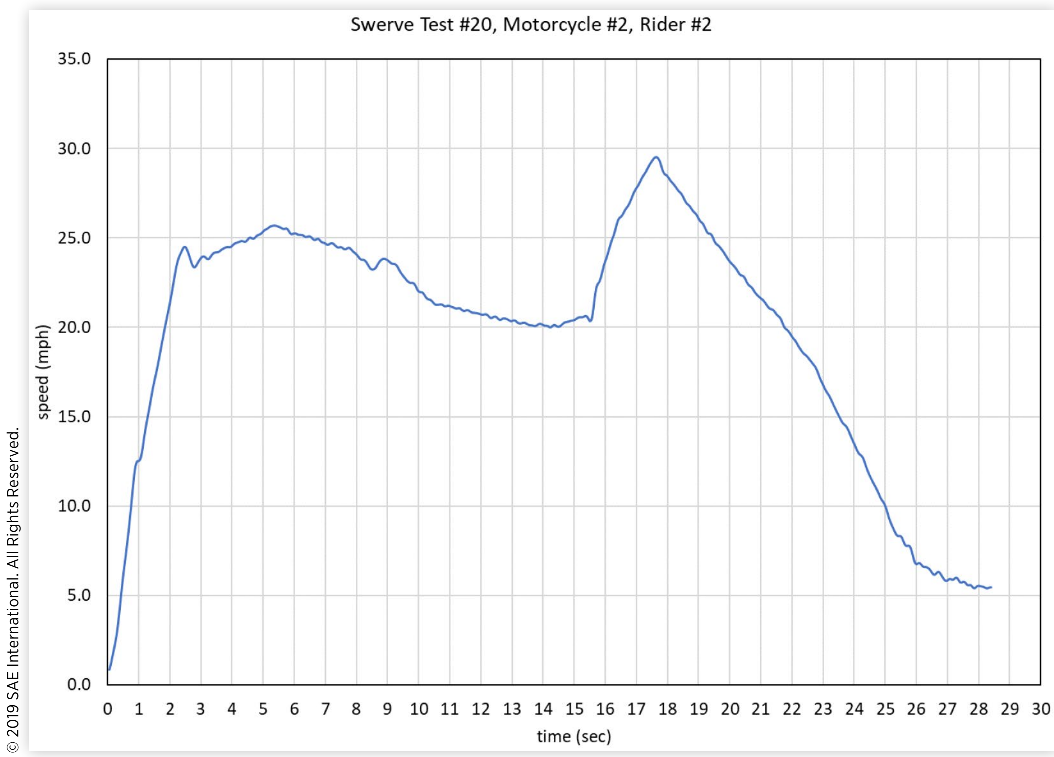


FIGURE B59 Lateral Acceleration, Swerve Test #20

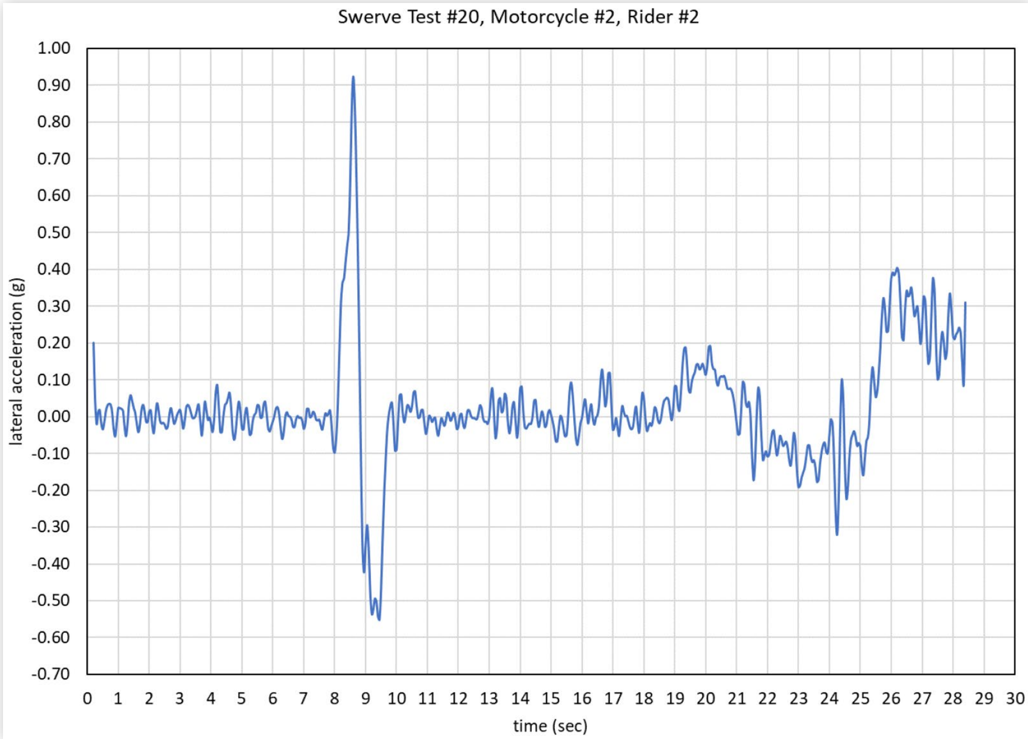


FIGURE B60 Heading, Swerve Test #20

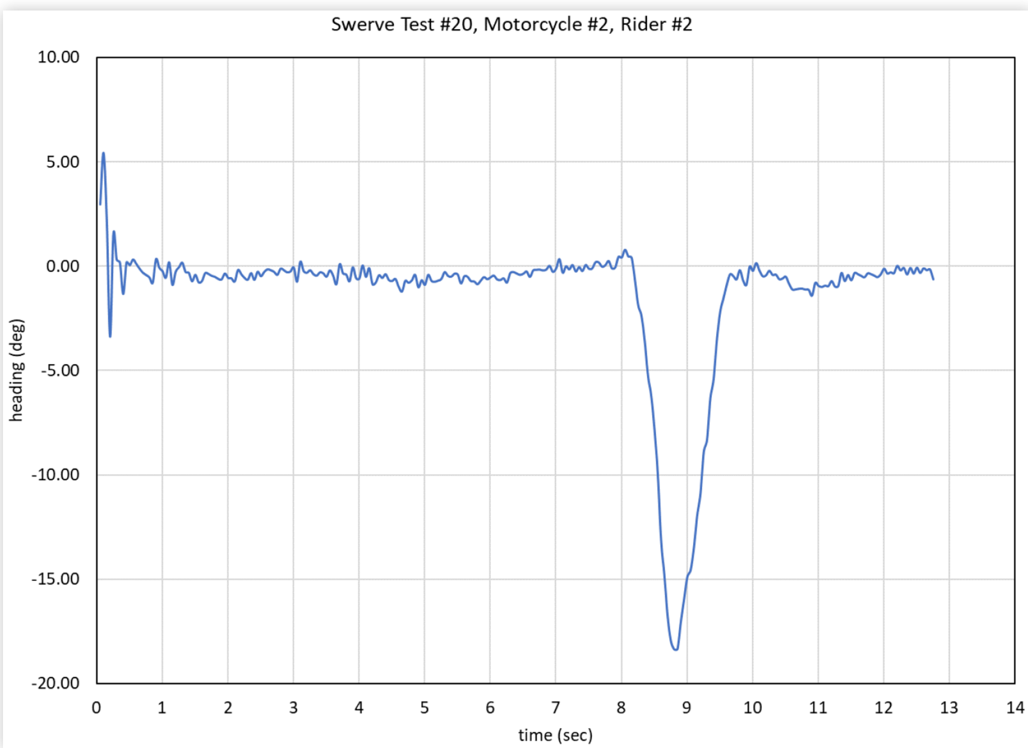


FIGURE B61 Speed, Swerve Test #21

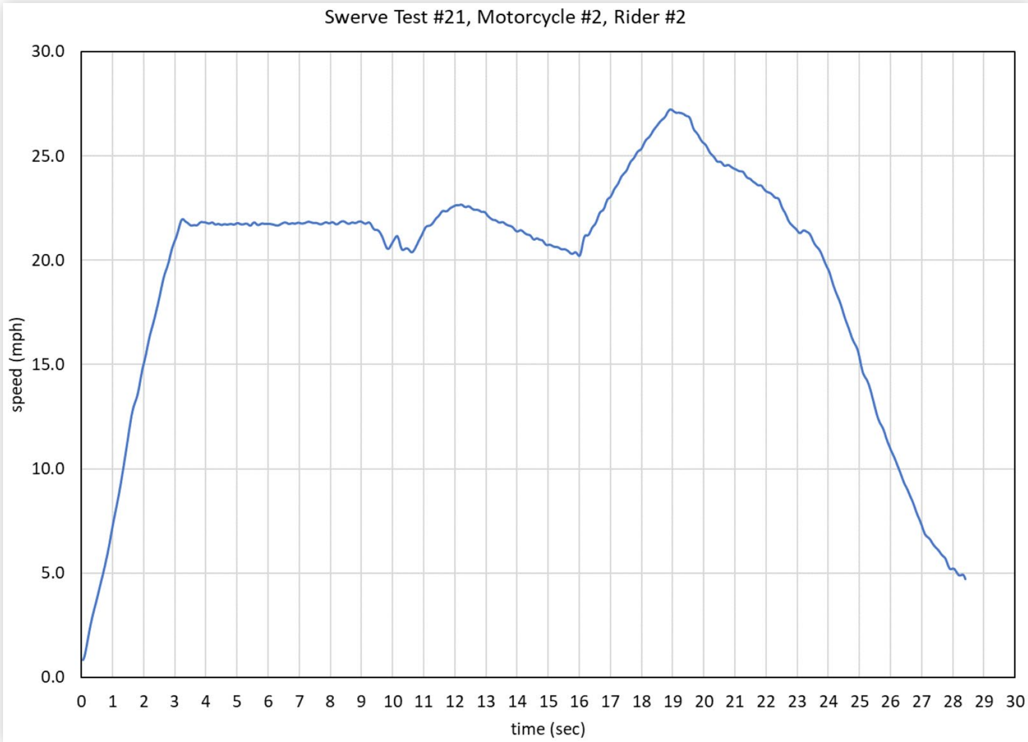


FIGURE B62 Lateral Acceleration, Swerve Test #21

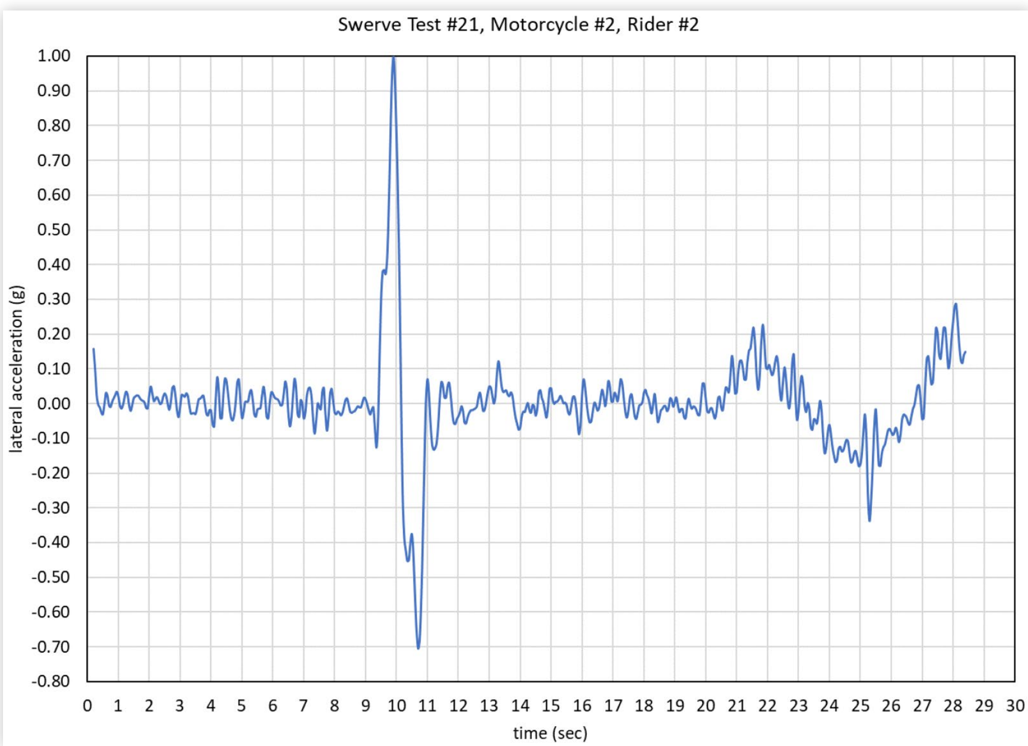


FIGURE B63 Heading, Swerve Test #21

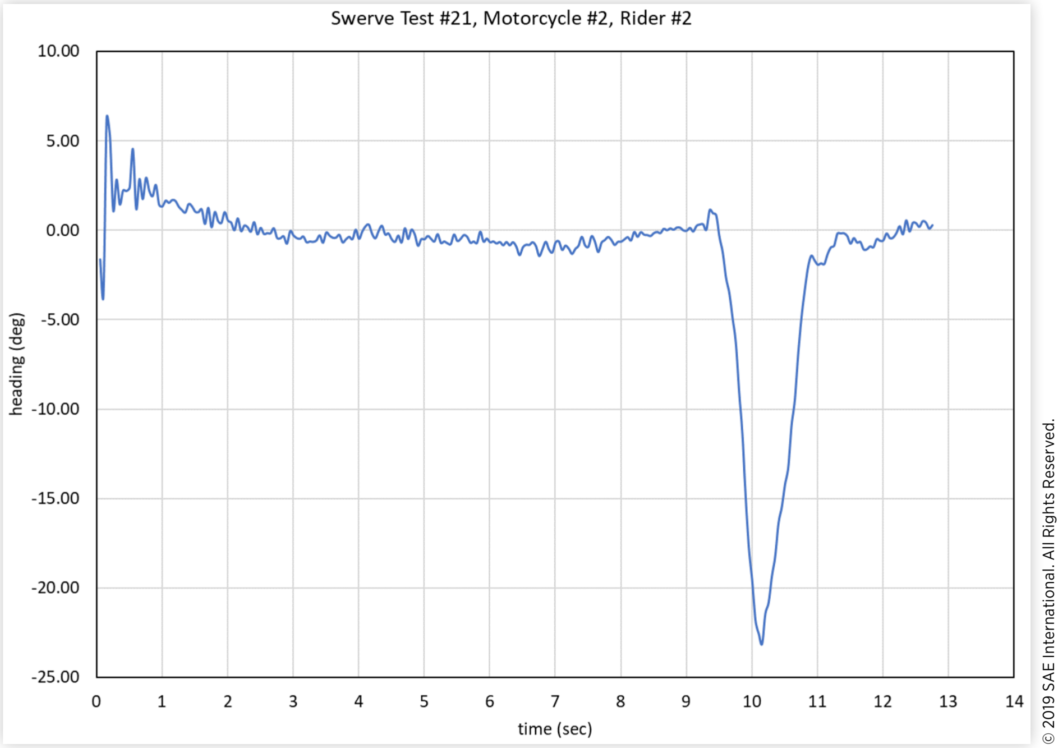


FIGURE B64 Speed, Swerve Test #22

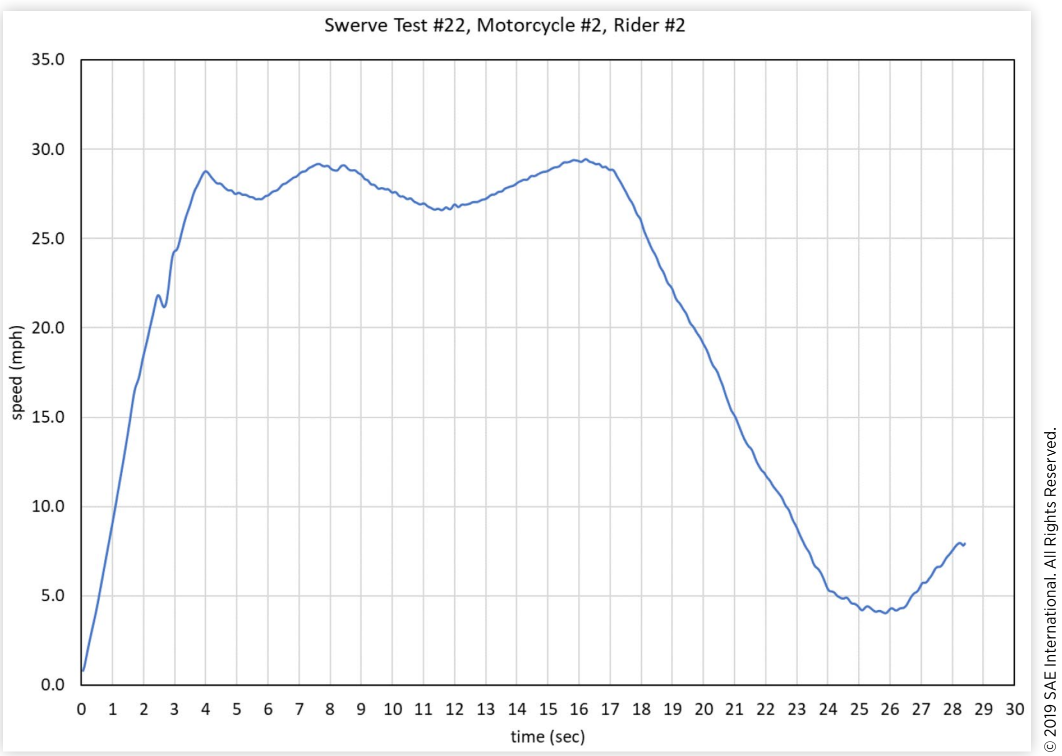


FIGURE B65 Lateral Acceleration, Swerve Test #22

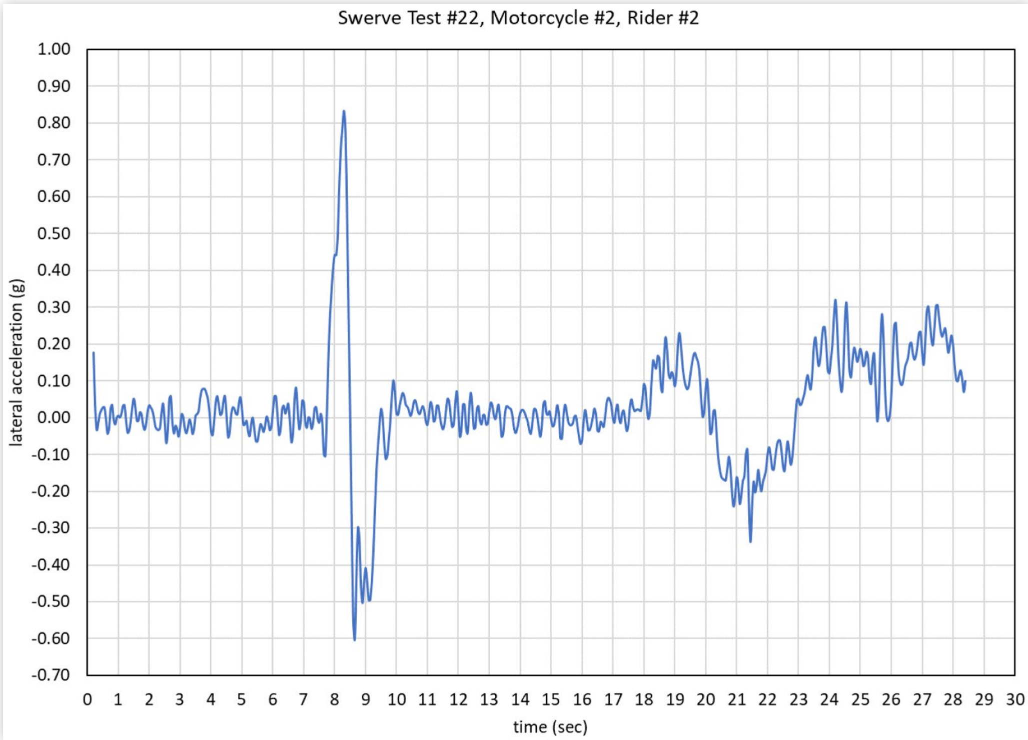


FIGURE B66 Heading, Swerve Test #22

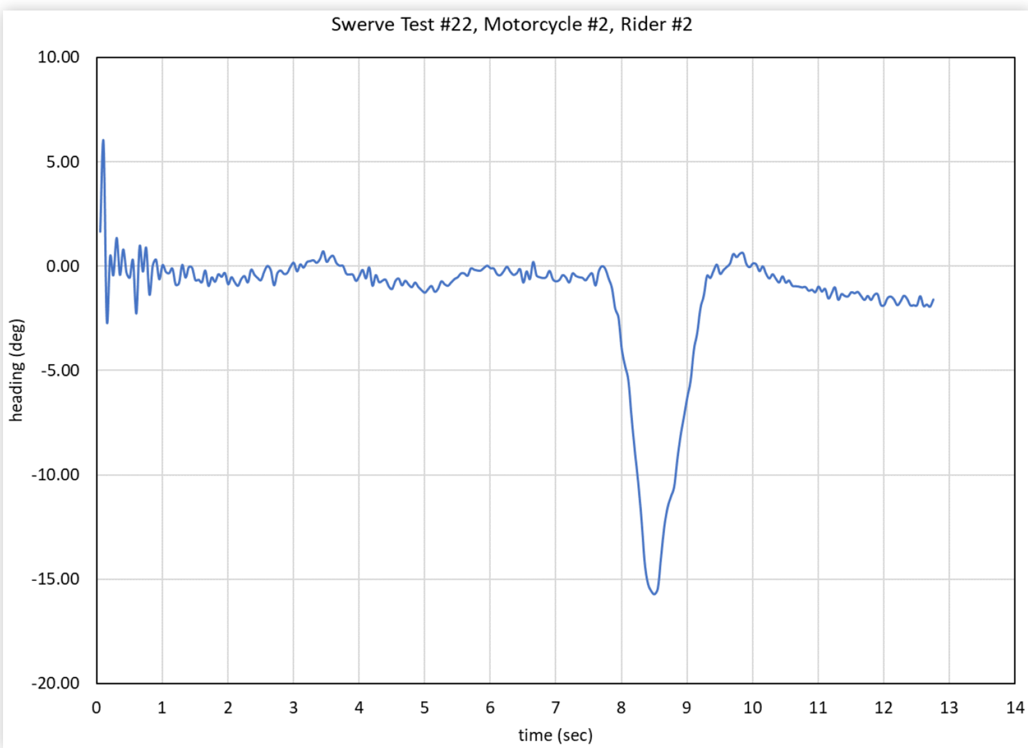


FIGURE B67 Speed, Swerve Test #23

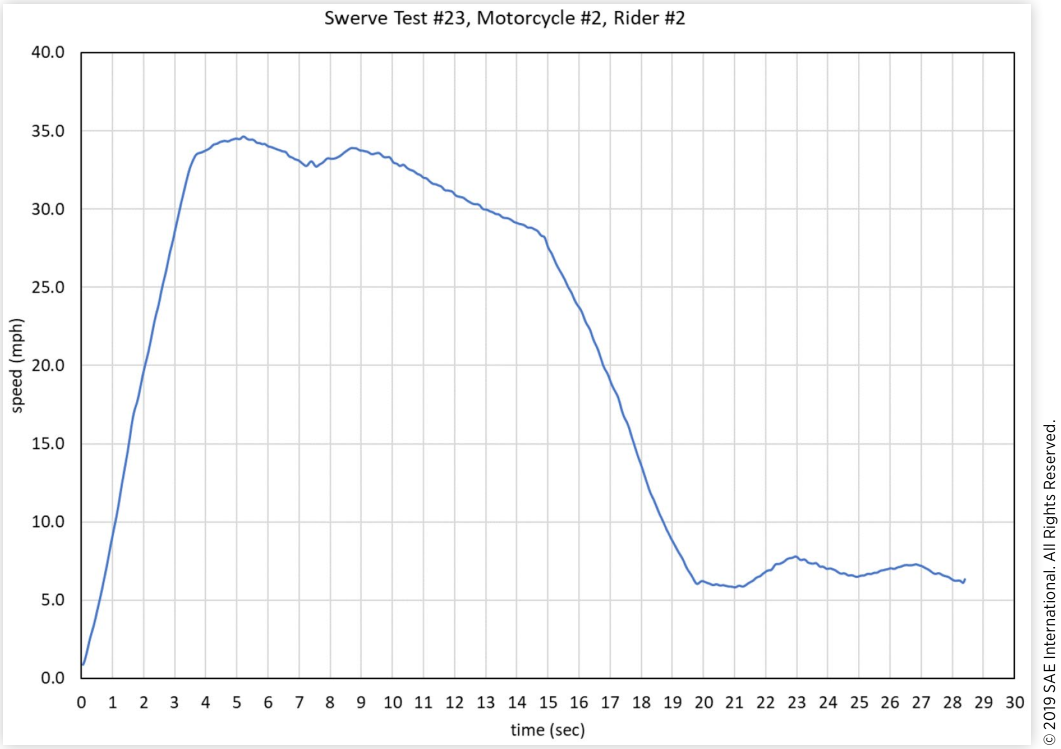


FIGURE B68 Lateral Acceleration, Swerve Test #23

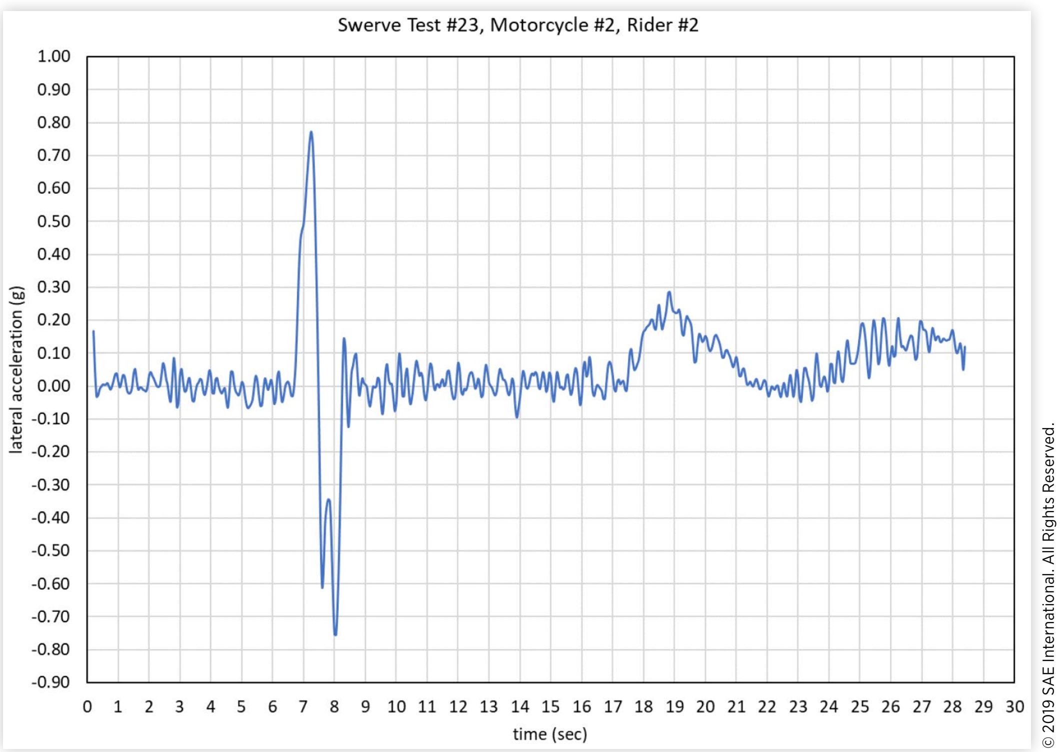


FIGURE B69 Heading, Swerve Test #23

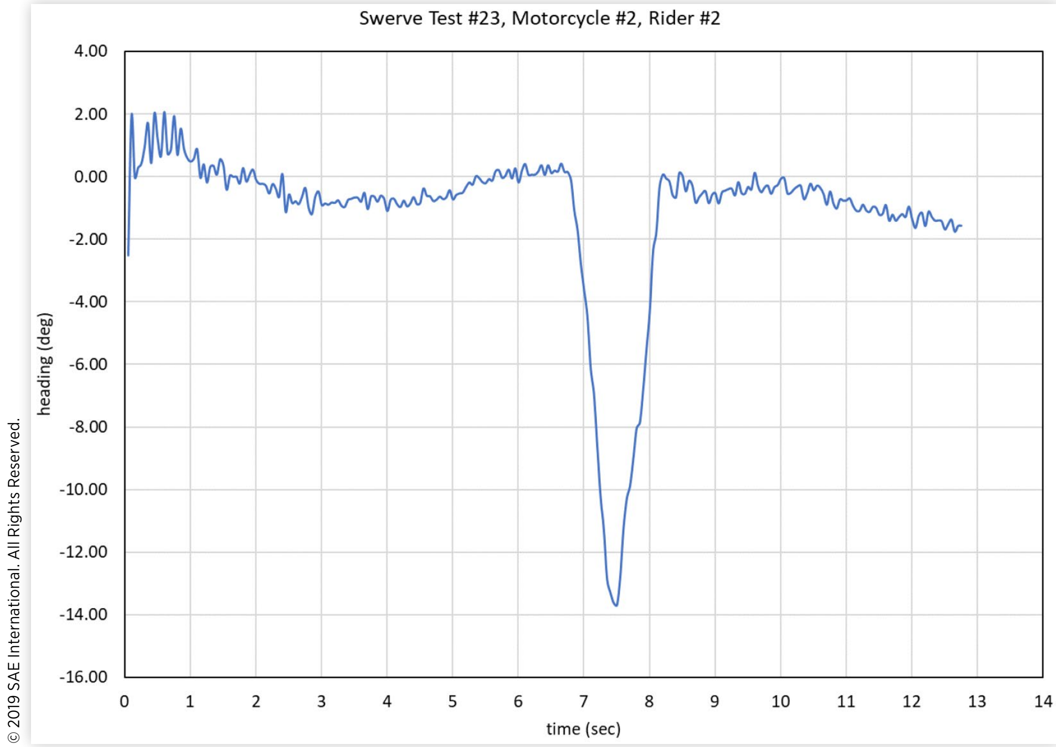


FIGURE B70 Speed, Swerve Test #24

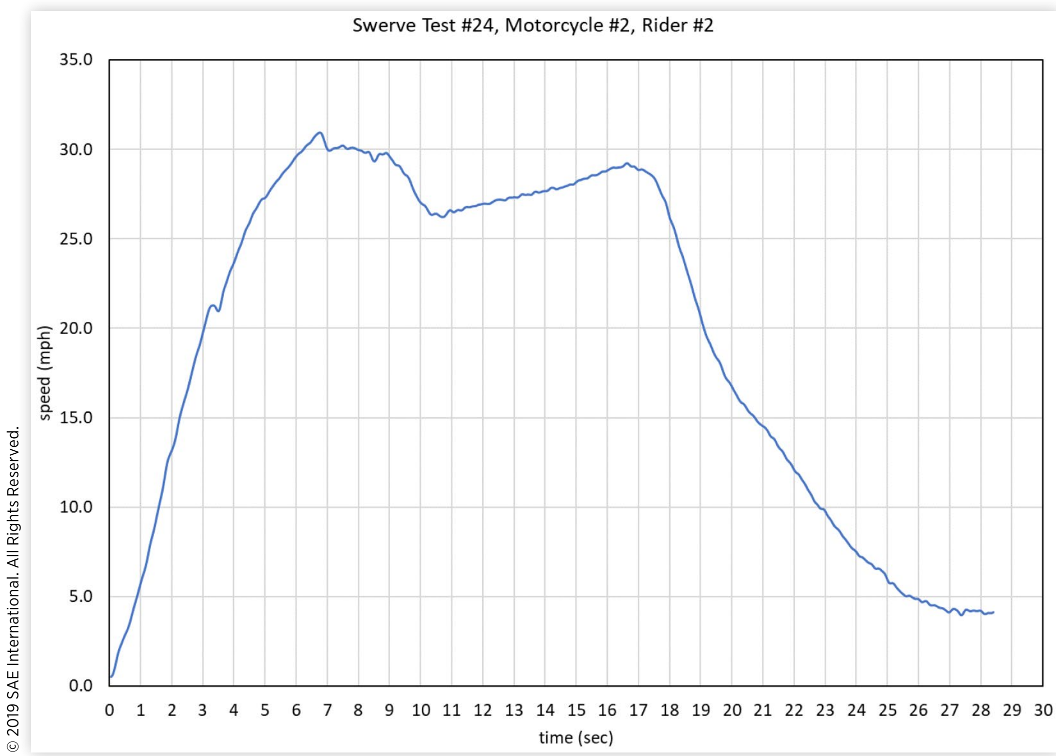


FIGURE B71 Lateral Acceleration, Swerve Test #24

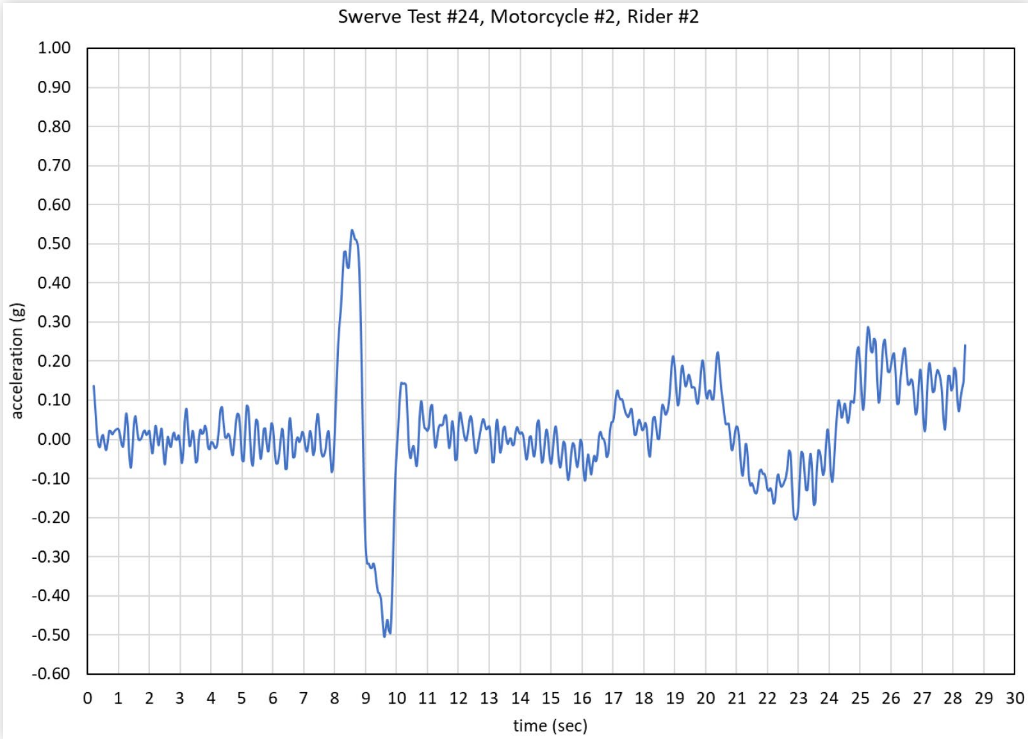


FIGURE B72 Heading, Swerve Test #24

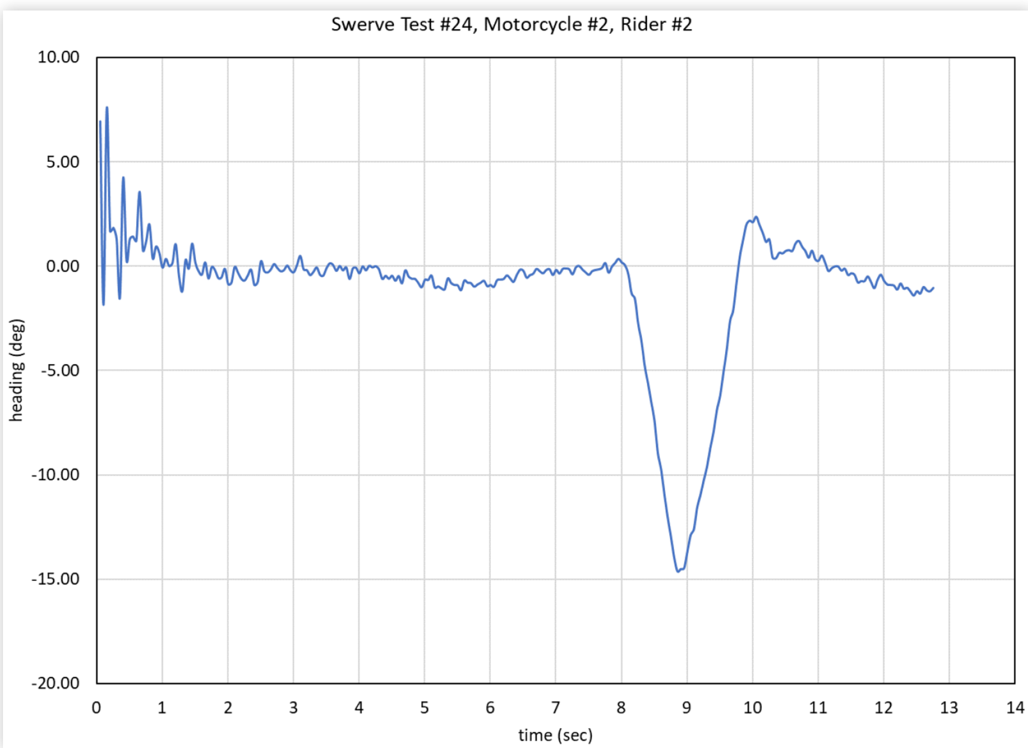


FIGURE B73 Speed, Swerve Test #25

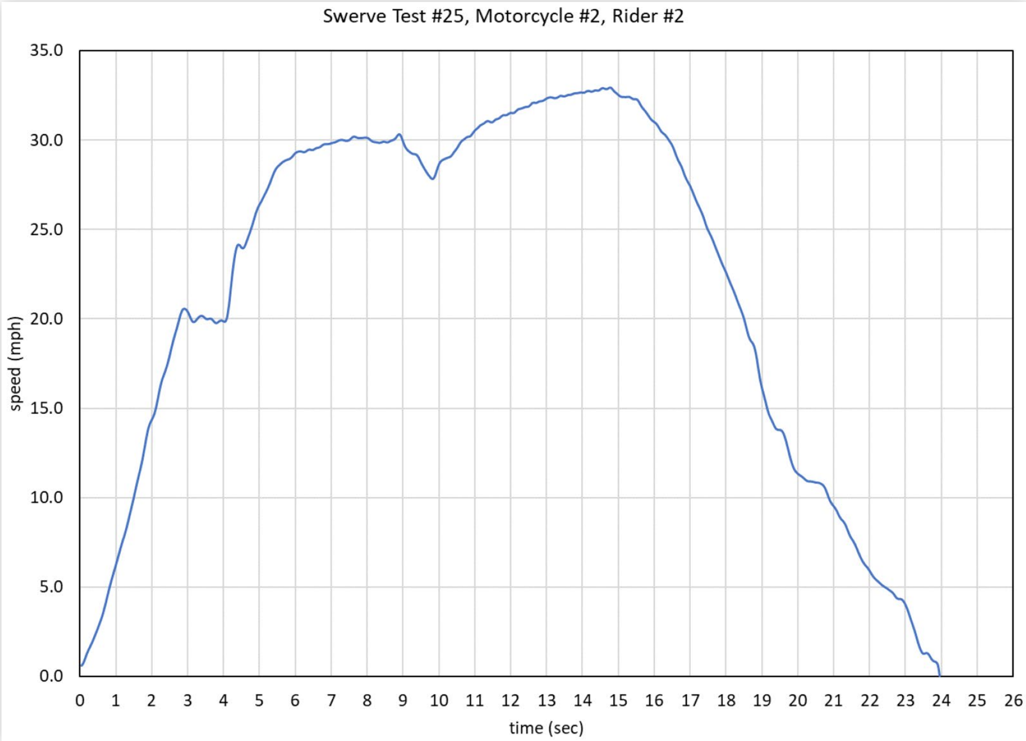


FIGURE B74 Lateral Acceleration, Swerve Test #25

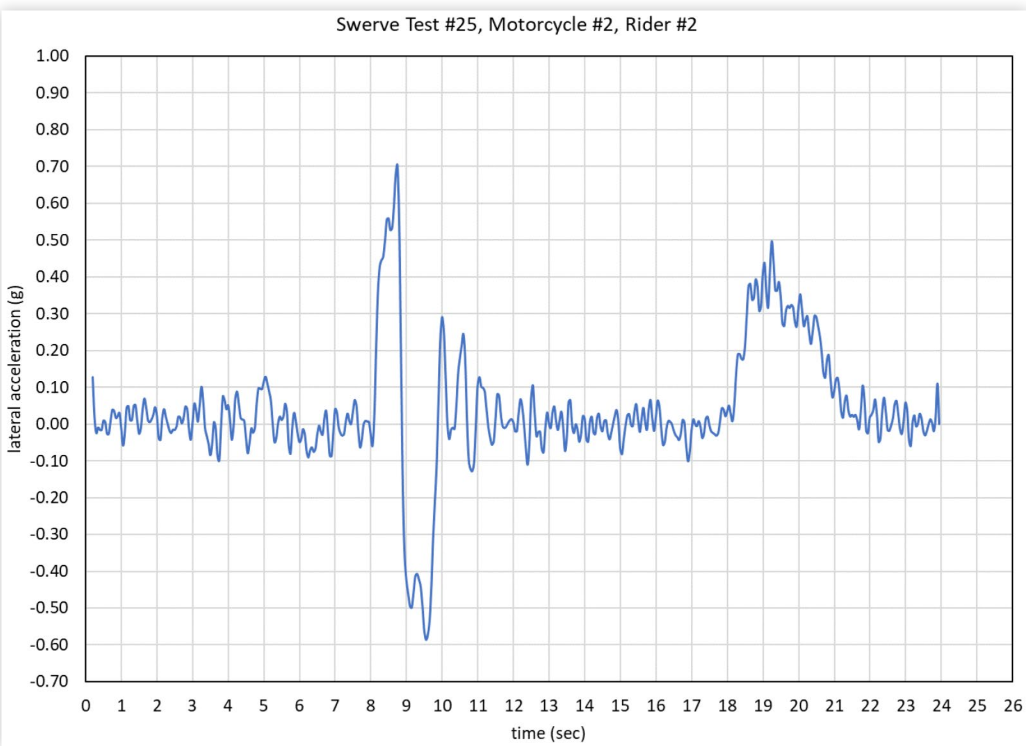
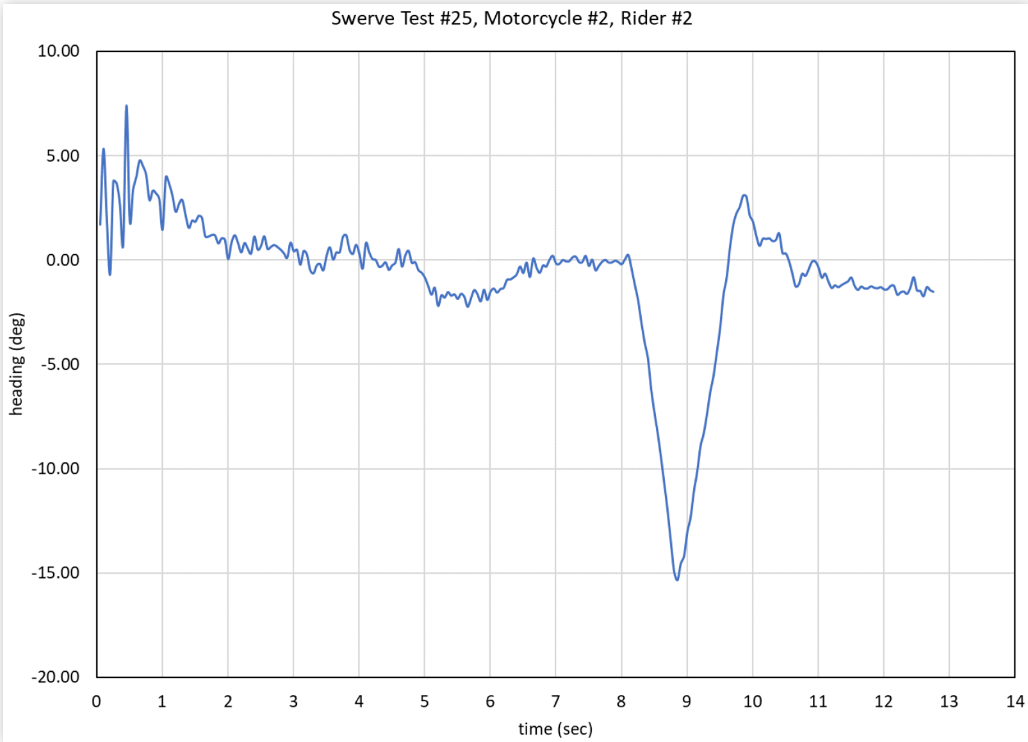


FIGURE B75 Heading, Swerve Test #25



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