REPEATABILITY OF THE CAROUSEL DYNAMIC STABILITY AND ROLLOVER TEST DEVICE

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Paper Number 19-0330

ABSTRACT

A novel test device (Carousel) for measuring the dynamic rollover stability of vehicles and initiating a full-scale dynamic rollover test has been installed and evaluated for repeatability and reliability. This work describes the test device function and presents results from preliminary repeatability testing. Both the test device and the test article were evaluated to objectively identify the repeatability between tests using correlation analysis. The results demonstrate that the fixture is capable of producing highly repeatable responses.

INTRODUCTION

Rollovers of passenger cars, vans, and light trucks not equipped with electronic stability systems in the U.S. are typically single-vehicle events (82.5%) initiated by a yaw followed by tripping (>80%) such as a furrowing, and gouging [1]. Vehicle rollover resistance ratings in the U.S. are determined by the National Highway Traffic Safety Administration (NHTSA) New Car Assessment Program (NCAP) using two methods; a static measurement of vehicle dimensions and a dynamic handling test. The static measurement method uses a vehicle's track width (T) and center of gravity (CG) height (H) to calculate a *static stability factor* (SSF) (Eq. 1). The vehicle's CG height is generally measured dynamically on a vehicle inertia measuring machine. A lower SSF indicates a higher risk of rollover [2], however more stable vehicles (higher SSF) have been shown to have higher injury risk during rollovers likely due to the increased speeds required to initiate a rollover [3]. The relationship between SSF and rollover risk has been shown to extend to smaller vehicles such as quad bikes [4] and larger vehicles such as heavy trucks [5].

$$SSF = \frac{T}{2H} \qquad \text{Eq. 1}$$

While the SSF does not account for the effects of tire design, suspension characteristics, wheelbase, effects of braking, or electronic stability control these parameters are considered during dynamic tests [2]. Depending on the scenario dynamic tests generally fall into two categories: closed-loop and open-loop maneuvers. Closed-loop maneuvers, such as the ISO 3888 double lane change, require all vehicles to follow a given path and are generally described as evaluations of vehicle maneuverability, not rollover resistance. Open-loop testing, such as the J-turn or fishhook maneuver, provides the same steering input for all vehicles and more frequently produces tip-up. While automated steering controllers are used to improve steering input repeatability, the complexity of the dynamic tests provide challenges in repeatability and reproducibility due to variations in environmental factors (e.g. temperature, humidity), road surface friction and finish, effects of safety outriggers, electronic stability control (ESC), and suspension age. Dynamic maneuver testing is much more expensive, time consuming, and potentially dangerous to drivers than static testing.

Centrifuge-style test methods were considered as an improvement to SSF in a NHTSA notice of proposed rulemaking that was generated in response to the Transportation Recall, Enhancement, Accountability and

Documentation (TREAD) Act of November 2000 [6]. Tests using this method are similar to the tilt-table and side-pull ratio tests and have been promoted for replicating rollover events initiated by both tripped or turn-over mechanisms [7]. The major drawbacks to a rollover rating system that solely used a centrifuge method include the potential for rewarding undesirable suspension characteristics (e.g. oversteer, roll stiffness distribution), lack of sufficient "dynamic" loading, and the fact that ESC would provide no benefit. Coupling a centrifuge test with a dynamic maneuver test would solve this issue. It is worthwhile to note that many manufacturers suggested that ESC be switched off for dynamic testing so that it couldn't be used to mask poor rollover resistance. The benefits of a centrifuge test include simple test setup, small test area, quick turnaround times, reliable tripping mechanism, insensitivity to pavement friction, and low cost of operation. The centrifuge test results would be expected to have a high correlation with SSF while improving the rating due to more realistic evaluation of the test article response by including vehicle load transfer and tire and suspension deflections. Concept tests conducted by the NHTSA at NASA's High Capacity Centrifuge facility demonstrated consistent liftoff values that were in agreement with expected lateral acceleration for rollover initiation.

The objective of this research was to evaluate and quantify the repeatability of a centrifuge-style test fixture (Carousel) with regard to both test fixture and test article response. While the device concept was born out of an interest related to vehicle rollover stability testing it can be applied to many other aspects of physical testing. The Carousel is simply a circular sled that could potentially be used in the same manner as traditional linear sleds following some modifications and/or additions such as a decelerator or test buck stand. The simplicity and compact nature of the device coupled with its high level of repeatability support its use in a wide range of applications.

METHODS

Two Series of tests without test article release were conducted; a Series of four (4) low-speed tests with no tip-up and a Series of four (4) high-speed tests with tip-up.

The test device, shown in Figure 1, consists of a stationary pivot at the center of a 5.4 m radius (approximate test article center) concrete circular track. A steel-framed wood-topped platform rotates about the stationary pivot and rolls on six (6) pairs of 20 cm wheels. The platform designed to accommodate a test article up to 2500 kg with track width and wheelbase not to exceed 1.7 m and 4.4 m, respectively. The device is powered pneumatically with on-board air stored in twin 0.227 m3 (60 gallon) pressurized tanks at a maximum pressure of 1240 kPa. The pressurized air is used to force two (2) pistons down parallel cylinders. The angular acceleration is controlled by the amount of air pressure. Each piston is attached to a steel wire rope that is wound around a central sheave which is rigidly attached to the stationary pivot. As the pistons are forced down the cylinders a torque is developed between the sheave and the platform which accelerates the platform around the track as the wire ropes unwind from the central sheave. The ratio of the central sheave circumference to wire rope length provides approximately 340 deg of angular acceleration. After the platform reaches a displacement of 340 degrees it coasts to a stop unless otherwise decelerated.

Figure 1 Test fixture with test article at start position

The test article was a 2000 Ford Ranger two-door super cab pickup with the dimensions and inertial properties summarized in Table 1. The test article is positioned on the platform with the transmission in ‘park’ and the parking brake engaged. Square aluminum tubes are positioned in front of and behind each tire and clamped to the platform to prevent fore-aft motion during the test. The outside faces of the outside tires are positioned in contact with trip bars. The trip bars consist of aluminum plates that pivot as they are loaded by the tires and the vehicle rotates over them as shown in Figure 2. Inside tire lift-off height is controlled with the used of chains affixed to the platform.

Table 1 Test article dimensions

Parameter	Value
Test weight / Distribution	1610 kg / 59 % front
Roll moment of inertia	638 kg m^2
Yaw moment of inertia	2661 kg m^2
Pitch moment of inertia	2628 kg m^2
Wheelbase	3.2 m
Track Width front/rear	1.5 m / 1.45 m
CG height	0.625 m
SSF	1.18
Tires	BF Goodrich All-Terrain 31x10.50R15 100s

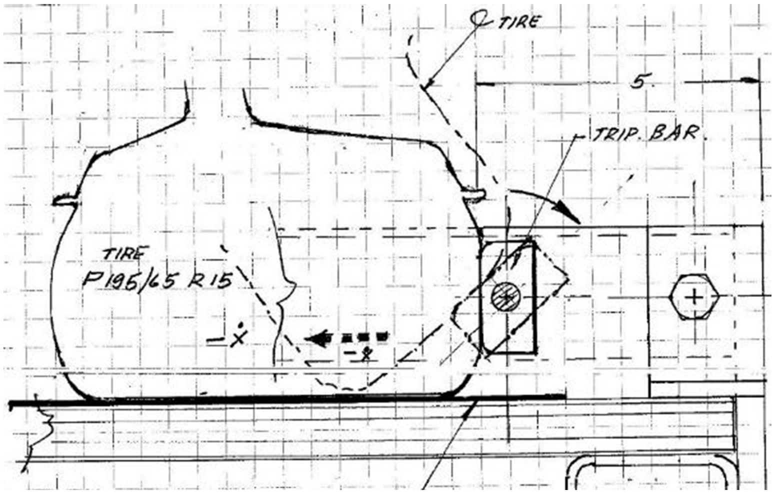

Figure 2 Cross-section view of tire and trip bar

A dual-output rotary potentiometer (Novotechnik RSC2832) was used to measure platform angular displacement. String potentiometers (Space Age Control 301432) were placed between the platform and the inside frame rail at the front and rear of the test article to measure the displacement of the test article during three of the Series 2 tests (Figure 3). The string potentiometer data in the fourth Series 2 test was erroneous and is not included below. Onboard real-time cameras were used to record each tire response and off-board cameras recorded the event from multiple angles.

Figure 3 Front (left) and rear (right) string potentiometer placement

The first Series of four (4) tests was selected to replicate a non-tip-up event. A test pressure of 689 kPa (100 psi) was expected to produce a test article lateral acceleration of approximately 0.6 g. The goal of the second test Series was to provide enough lateral acceleration to initiate a rollover. The second test Series comprised four (4) tests and used a tank pressure of 1034 kPa (150 psi). In all tests the inside tires of the test article was restrained to allow for a maximum lift of approximately 75 mm. A summary of the test conditions is provided in Table 2.

Table 2 Test summary

Test Series	Test parameters	Goal values
1	Tank pressure	689 kPa (100 psi)
	Test article lateral acceleration	0.6 g
	Peak platform velocity	60 deg/s
	Number of tests	4
2	Tank pressure	1034 kPa (150 psi)
	Test article lateral acceleration	1.1 g
	Peak platform velocity	80 deg/s
	Number of tests	4

The tests were conducted over a two-day period from 10 am to 6 pm each day. The weather was stable with temperatures ranging from 25 to 37° C (77 to 99° F) and humidity ranging from 84 to 35 % between the morning and afternoon. Multiple warmup and practice runs were performed prior to conducting the test Series to ensure that the moving parts of the test fixture and test article had loosened up. After the initial setup and practice runs were complete the test runs in each test Series was completed consecutively within 90 minutes from start to finish.

Correlation analysis (CORA) was utilized to objectively compare the platform angular displacement and the test article displacement in each test to the average values for a given test Series. CORAplus version 4.04 with recommended global settings was used to calculate the scores using the cross correlation method. Curves were filtered according to J211 recommended protocol.

RESULTS

At test initiation the accelerating platform produced a slight rearward pitching motion of the test article which can be seen in the initial negative displacement of the rear string pot data. As the platform angular velocity increased the vehicle began to roll outboard. None of the tires lifted off of the platform in the Series 1 tests. The goal test conditions were achieved in all tests.

The platform angular displacement time history matched very well between tests in a given series as shown in Figures 4 and 5. The average maximum angular velocity for each test series was 60.1 deg/s and 79.25 deg/s. On average, the platform reached 340 deg of displacement (end of angular acceleration) in 9.7 seconds and 7.6 seconds in test series 1 and 2, respectively.

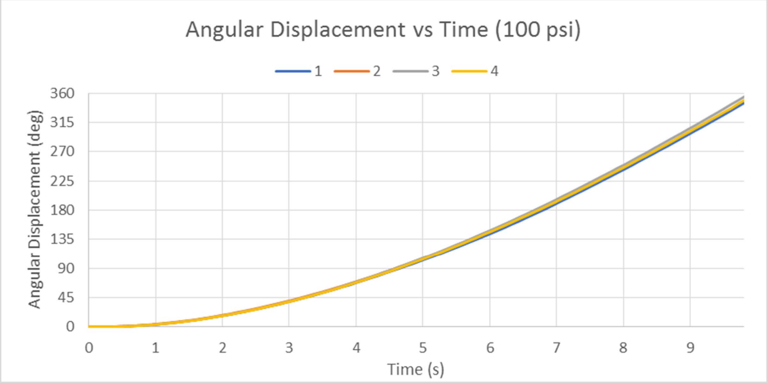

Figure 4 Platform angular displacement time-history (Test Series 1)

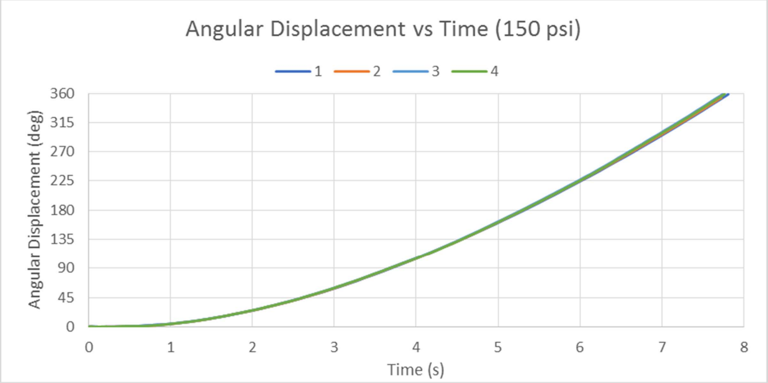

Figure 5 Platform angular displacement time-history (Test Series 2)

Test article displacement was consistent between tests as shown in Figures 6 and 7. String potentiometer data from the fourth Series 2 test was erroneous is not included here. The average maximum displacement at the front and rear string potentiometer locations was approximately 31 mm and 47 mm, respectively. The values correspond to the maximum displacement allowed by the tie-down chains. In the Series 2 tests the front and rear tires lifted off at approximately 4.5 and 7.7 seconds, respectively. The video footage indicates that a difference in chain response in Test 2 is likely the reason for the relatively large difference in displacement for that test.

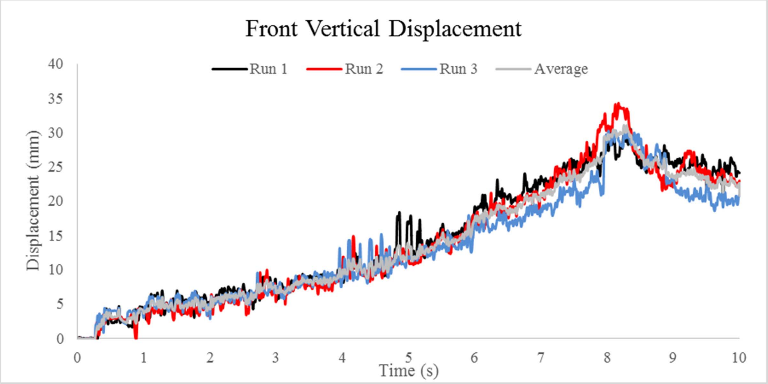

Figure 6 Test article displacement time-history (front; Test Series 2)

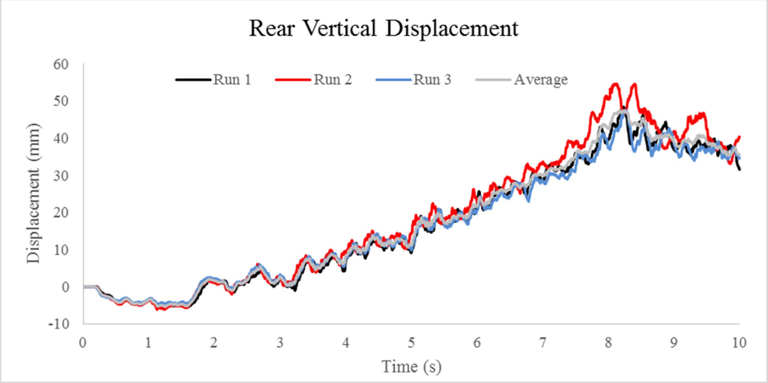

Figure 7 Test article displacement time-history (rear; Test Series 2)

The results of the CORA analysis are summarized in Table 3. Values above 8.6 are considered to indicate excellent repeatability.

Table 3 CORA results summary

Test Series	Measurement	Test	Cross correlation rating – per test				Total Series rating
			Cross correlation	Size	Phase shift	Total	
1	Platform displacement	1	1.0	0.966	1.0	0.992	0.995
		2	1.0	0.984	1.0	0.996	
		3	1.0	0.974	1.0	0.993	
		4	1.0	0.993	1.0	0.998	
2	Platform displacement	1	1.0	0.997	1.0	0.999	0.998
		2	1.0	0.978	1.0	0.994	
		3	1.0	0.987	1.0	0.997	
		4	1.0	0.999	1.0	1.0	
2	Test article displacement (rear)	1	0.994	0.937	1.0	0.981	0.968
		2	0.990	0.845	1.0	0.956	
		3	0.993	0.884	1.0	0.968	
2	Test article displacement (front)	1	0.987	0.939	1.0	0.978	0.975
		2	0.986	0.946	1.0	0.980	
		3	0.984	0.90	1.0	0.967	

DISCUSSION

The test fixture and test article demonstrated excellent repeatability for the two test series evaluated above. After initial test setup, tests could be performed with two technicians and 45 minute turnaround times. The greatest time-cost between tests included re-pressurizing the system and downloading the data. During test setup it was observed that initial ‘warm-up’ runs would be required to exercise both the fixture and the test article such that all joints and suspensions were loosed up and would perform consistently.

The lowest levels of repeatability were related to test article performance, though the repeatability was still considered excellent. This was expected as the test article introduced many additional characteristics that could affect response such as suspension and tire properties that could vary with changes in temperature or use. One proposed method to limit the effects of tire characteristics is to define a standardized tire or tire surrogate that would be used for all vehicles and provide a consistent interface between the tire and the trip-bar.

Some lateral motion of the test article was expected based on the results of a similar test series conducted by the NHTSA at National Aeronautics and Space Administration’s High Capacity Centrifuge [8], however no custom mechanisms were created to account for this with regard to the string pot measurements. It is anticipated that future rollover stability testing will require the use of custom-designed load cell mounts that move laterally with each tire. The lateral motion of the vehicle during initial warm-up testing and subsequent calibration testing presents a challenge in identifying the initial position of the vehicle for a test. Differences in the initial lateral position of the vehicle, specifically regarding pre-loading against the trip-bar, could potentially alter the performance. Lateral positioning of the vehicle during initial setup proved challenging and pre-loading the outside tires against the trip-bar was not possible. A pre-load could be applied by conducting one or more low-speed tests, however variations in the suspension spring back were observed after the platform came to rest.

While this paper has focused on using the Carousel to evaluate the dynamic rollover resistance of a passenger vehicle it could easily be extended to evaluating all-terrain vehicles (ATVs) and side-by-side vehicles. The device has the potential to evaluate restrain performance under varying yaw and roll rates in a repeatable, safety, and non-destructive manner. The platform can be modified with addition of a deformable barrier face to apply impact loads to stationary test articles. Various high- and low-rate deceleration mechanisms have been proposed that would allow the Carousel to perform as a traditional non-destructive deceleration sled.

CONCLUSIONS

A centrifuge-style test device (Carousel) was described. The performance of the Carousel and the response of a test article were evaluated to quantify their repeatability under low and high-speed test conditions. The Carousel and the test article both demonstrated excellent repeatability according to cross-correlation analysis using the CORA methods. The results demonstrate that the device is a suitable candidate for performing repeatable dynamic stability tests.

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