

Full-Scale Testing and Analysis of Tractor-Trailer Braking Performance With and Without Trailer Anti-Lock Brakes

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ABSTRACT

Anti-lock brakes have been implemented on tractor-trailer units for several years. However, a fatal accident involving trailer swing indicated that there is some disagreement within the accident reconstruction industry as to what effects trailer anti-lock brake systems have on the stopping performance, dynamic performance/handling of the trailer, and resultant skid marks left on the roadway. Full-scale testing was conducted on a tractor-trailer unit which was equipped with anti-lock brakes on both the tractor and trailer. Full application braking tests were performed from 65-70 mph concurrent with a lane change. Baseline tests were conducted with all anti-lock systems operational, and the tire marks, amount of trailer swing, and stopping distance were recorded. The test was then repeated with the trailer anti-lock brakes disabled. All tests were videotaped from three positions: a stationary camera at the end of the test run, a stabilized camera mounted on a chase vehicle, and a stabilized camera mounted on the driver's side of the tractor cab facing aft. Results showed the types of marks left by tires both with and without anti-lock brakes. The tests also provided qualitative indications as to the effect of locked trailer tires on trailer swing. The measured stopping distance was also used to calculate an overall deceleration rate for the tractor-trailer, and this deceleration rate was then compared to speed-time data recovered from the tractor's engine control module.

INTRODUCTION

A fatal accident involving a tractor-trailer unit occurred on a major interstate in the western U.S. The tractor-trailer was travelling at approximately 66 mph in the right-hand travel lane when it came upon traffic which was stopped for a previous accident. The tractor-trailer driver initiated maximum braking and swerved onto the right shoulder of the

interstate. While the tractor avoided contact with the stationary traffic in front of the tractor, the trailer rotated clockwise. The trailer undercarriage subsequently struck a stopped vehicle, propelling the vehicle into the rear of a stopped tractor-trailer. During the subsequent investigation, questions arose as to whether or not the trailer's anti-lock brake system was functional during the accident sequence. The purpose of the testing reported in this paper was to determine the effect of trailer ABS on the type of marks left by the trailer.

ACCIDENT SEQUENCE

The marks left by both the tractor trailer and the car were photographed and documented by the state police, as well as the points of impact and points of rest of the vehicles. The path of the vehicles is shown in [Figure 1](#).

The marks left by the trailer are shown in [Figure 2](#).

During the accident, the trailer rotated clockwise approximately 15 degrees during the braking/steering maneuver. At some point during the sequence, the undercarriage pins released and allowed the undercarriage to slide aft with sufficient force to damage the ICC bar as shown in [Figure 3](#).

Two theories were presented during the investigation. One was that the undercarriage slid aft due to the pins not being fully locked. When the undercarriage contacted the ICC bar, it dislodged from the rails. It was postulated that the marks subsequently left by the trailer were due to the rotation of the trailer bogie relative to the trailer chassis after it left the rails, and that the ABS had functioned as designed. Furthermore, the gaps in the initial tire marks ([Figure 2](#), left) were attributed to ABS cycling as opposed to wheel hop. However,



Figure 1. Accident sequence

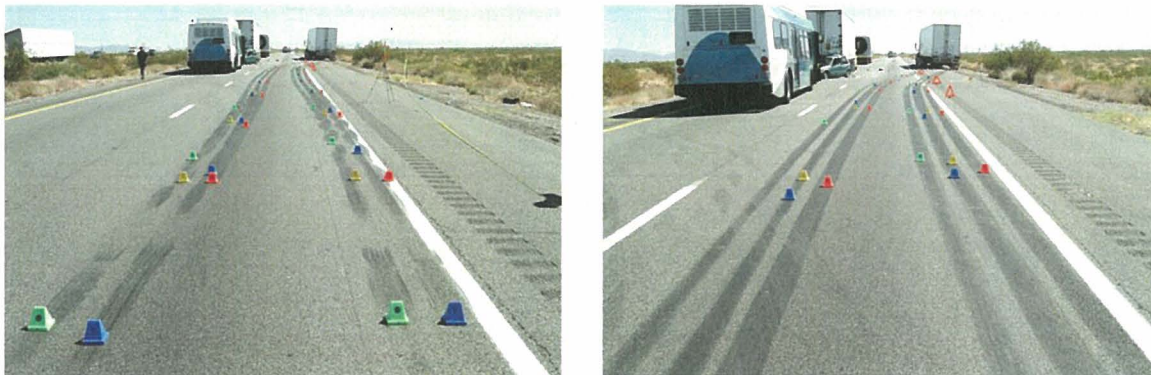


Figure 2. Marks left on roadway by trailer.

the undercarriage rotated clockwise when it left the rails, therefore, any dog tracking would have pulled the trailer to the right, not to the left. Furthermore, the State Police report alleged that the bogie slid aft due to impact with the stopped vehicle. Therefore, the marks deposited in [Figure 2](#) would have been made prior to any bogie displacement.



Figure 3. Damage to rear of trailer due to undercarriage motion.

The other theory was that the ABS was not functional, and that the trailer swing was a result of the locked trailer wheels. While there is literature that shows the difference in skid marks deposited by vehicles with and without ABS, the majority of such work applies to passenger vehicles with

hydraulic brakes. [1,2] Therefore, full scale testing was performed to document the differences in marks produced by a trailer with and without ABS as well as to determine which explanation was most likely.

TESTING

Testing was performed on an abandoned runway using a 2005 Freightliner Columbia with Caterpillar C-15 engine, and a WABCO 4S-4M ABS module on the drive wheels. The tractor's GVW at the time of the accident and at testing was 16,900 lbs. The trailer was a 1998 Great Dane 53 foot box trailer with a WABCO 4S-2M ABS module and an empty weight of 15,420 lbs. At the time of the accident, the trailer contained approximately 33,000 pounds of miscellaneous cargo. However, the location of the cargo and pallets at the time of the accident was not known. Therefore, the trailer was loaded with 33,000 lbs of cinder blocks distributed uniformly in the trailer. The tractor-trailer was weighed prior to testing, and the following axle weights were measured: steer axle - 9,620 lbs; axle 3/4 - 26,280 lbs, axle 4/5 - 29,420 lbs. The GVW for the test vehicle was 65,320 lbs.

A series of test lanes were marked on the runway using adhesive reflectors. The test vehicle was driven down the runway at a speed of approximately 66 mph, which was confirmed by radar. Cones were placed along the lane to indicate the point at which the driver was to apply full braking and begin the swerve to the right. Cones were also placed approximately 75 feet from the initiation point to define the point at which the tractor needed to be clear (to the



Figure 4. Test cameras mounted on tractor and chase vehicle.



Figure 5. Braking marks with trailer ABS on.

right) of the travel lane. These marks corresponded to the documented path of the tractor-trailer from the accident.

After each test run, the Caterpillar Engine Control Module (ECM) was downloaded to preserve the Quick Stop data, and the resulting tire marks were measured as a prelude to calculating the average deceleration rate for the tractor-trailer.

Each test run was videotaped from a stationary camera placed at the end of the test track. Each run was also filmed by a stabilized camera mounted to a chase vehicle as well as a third camera mounted to the driver's side of the tractor facing aft. Vehicle mounted cameras are shown in [Figure 4](#).

TIRE MARKS - ABS ENABLED

The test procedure called for the driver to approach the marking cones at approximately 66 mph. Once reaching the cones, the driver applied full braking and initiated a swerve to the right. Based on documented marks at the accident scene,

the tractor was clear of the travel lane in approximately 75 feet. The first several tests were performed with the trailer ABS system activated. The resulting marks are shown in [Figure 5](#).

As shown in [Figure 5](#), the trailer with ABS deposited solid, although light, marks throughout the stop, and these marks were very similar to those deposited by the tractor, which had a functioning ABS system. Also, the marks documented at the accident scene as being deposited by the tractor were also light, "shadow" marks similar to those shown in [Figure 5](#). Therefore, these tests confirm that with a functioning ABS, a tractor-trailer will tend to deposit light skid marks throughout the stop.

During these tests, the trailer swung clockwise approximately 2-3 degrees, and had a maximum off-track (defined as the maximum lateral distance between the tractor tire marks and the trailer tire marks) of 1.5 - 2 feet. Four tests were



Figure 6. Tire marks from first test with ABS disabled.

performed with the trailer ABS enabled, and the trailer marks measured from 262 - 293 feet, with the distance increasing with each test. The four tests were performed in a span of 1 hour. Therefore, it is likely that the steady increase in stopping distance could be attributed to changes in tire temperature or wear/conditioning during the tests.

TIRE MARKS - ABS DISABLED

The trailer ABS was disabled by disconnecting the plug to the module, and the braking tests were performed. On the first test with the ABS disabled, the trailer swung clockwise approximately 3-4 degrees when the swerve was initiated. However, as the driver steered left after the swerve to align with the lanes, the trailer swung counterclockwise approximately 8 degrees. In other words, as the tractor was steered left the trailer swung completely across the path of the tractor and was angled to the right of the tractor at rest. The marks from the first test are shown in [Figure 6](#).

It was noted that the left side marks (shown in [Figure 6](#)) seemed to indicate that only one set of duals on the left side of the trailer were locked. Analysis of the video taken by the chase vehicle during testing showed that the left wheels of the #4 axle failed to lock during brake application. Therefore, the one rolling set of duals provided sufficient cornering force for the trailer to track through the initial lane change with the tractor. However, once the weight shifted to the right side sets of duals, which were both locked, there were no cornering forces developed. Therefore, the trailer swung counterclockwise through the end portion of the lane change.

The testers were informed at that time that the brake canister and pads on the left side of the #4 axle had been replaced

before the testing. The pushrod was well within adjustment, therefore, it was decided to adjust the trailer load in order to reduce the normal force on the wheels in an attempt to get all four brakes on the trailer to lock. After the load shift, the trailer axle weights (axle 4/5) were measured as 24,060 lbs. This weight shift allowed all wheels of the trailer to lock during brake application.

Subsequent tests with the ABS disabled produced the tire marks shown in [Figure 7](#).

As shown in [Figure 7](#), the trailer with ABS disabled deposited solid marks throughout the stop. The trailer swung clockwise approximately 12-13 degrees, and had a maximum off-track (defined as the maximum lateral distance between the tractor tire marks and the trailer tire marks) of 8.5 - 9 feet. Two tests were performed with the trailer ABS disabled, and the trailer marks measured from 274 - 296 feet.

One key marker for the amount of trailer swing in the subject accident was the fact that the trailer tires started out as a set of two parallel lines, which one would expect from locked dual tires. However, at the point of maximum trailer swing, a set of three parallel tire marks were observed. This was due to the angle of trailer rotation, which placed the inside tire of axle #5 in line with the outside tire of axle #4. This phenomenon was observed during testing when the trailer ABS was disabled. The tire marks from the accident and testing are shown in [Figure 8](#).

Due to the unknown load configuration during the accident as well as the road surface differences (runway versus a highway), the fact that the trailer swing observed during testing was very close to that seen during the accident should



Figure 7. Tire marks from trailer with ABS disabled.



Figure 8. Tire marks due to trailer swing from accident (left) and testing (right).

only be viewed in a qualitative sense. In other words, the tests indicate that with locked wheels, the trailer does in fact obey Newton's laws and attempts to travel in a straight line.

Therefore, the testing indicated that in the absence of ABS, the trailer would leave dark, solid lines due to wheel lock throughout the braking distance. This also suggests that the gaps in the skid marks left by the accident trailer at the beginning of braking were likely due to trailer hop. Furthermore, the amount of trailer swing observed during testing with the ABS enabled versus the amount of swing with the ABS disabled indicated that the ABS was not functioning during the accident sequence. Whether the ABS on the accident trailer was never functional at the time of the accident or whether it was disabled by the undercarriage sliding aft could not be determined. Nevertheless, the testing supports the hypothesis that the marks deposited by the trailer during the accident were due to a non-functional ABS, and were not the result of non-locked tires that were dog tracking.

STOPPING PERFORMANCE

Calculated Test Deceleration Rate

The deceleration rate for the tractor-trailer during testing was calculated with the following formula:

$$a_g = \frac{V^2}{30D}$$

Where:

a_g = acceleration (g's)

V = vehicle speed at start of braking (mph)

D = length of tire marks during braking (ft)

Table 1. Calculated deceleration rates for 6 tests.

Test Number	Vehicle Speed (mph)	ABS State	skid mark length (ft)	Deceleration Rate (g's)
1	66	ON	262	0.55
2	66	ON	266	0.55
3	66	ON	278	0.52
4	67	ON	293	0.51
5	66	OFF	274	0.53
6	66	OFF	296	0.49

Test 1 ABS On

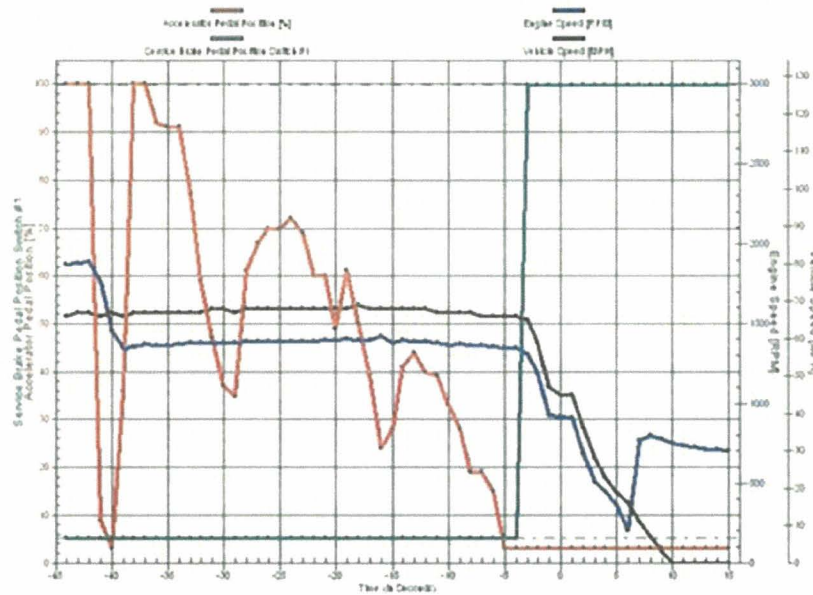


Figure 9. Example plot from ECM download.

The calculated deceleration rates for the 6 tests are shown in Table 1.

As shown in Table 1, the average deceleration rate for the tractor-trailer was approximately 0.53 g's with ABS, and 0.51 g's with the ABS disabled. Therefore, the deceleration rate is relatively unaffected by the performance of the trailer ABS. This makes sense since the trailer contribution to overall braking is less than that of the tractor axles due to weight shift during deceleration.

Test Deceleration Rate From ECM Data

As discussed above, after each test run, the Caterpillar ECM from the tractor was downloaded to record the Quick Stop data. The results of the download were provided to the authors in a graphical format as shown in Figure 9.

In calculating the average deceleration rate from the ECM data, the authors noted two problems with the data. First, on

each test plot, it appeared that the tractor-trailer required more than 12 seconds to slow from 66 mph to a stop with full braking. This time required to stop did not agree with the time recorded on the captured video. Furthermore, the rate of deceleration calculated directly from the graphs was significantly lower than that observed from the measured skid marks. The root of this problem was identified as a software issue with the Caterpillar ECM [3]. When some units of the Caterpillar ECM print out the recorded data, the time scale is off by a factor of 2. This phenomenon has been documented and explained in the literature [3]. The solution is to reduce the time scale by 1/2, or in other words, the time during testing from brake application to stop should be cut in half. This agrees with the timing shown on the captured video.

The second issue identified in the ECM plots is that on each test download, the velocity plot showed a leveling, or in some instances an increase, in speed approximately 1 second after brake application. (Time given is corrected for the ECM plot



Figure 10. Tractor wheel lift during lane change.

Table 2. Comparison of Deceleration Rates Calculated From Skid Marks and ECM Data.

Test Number	Deceleration Rate Skid Marks (g's)	Deceleration Rate ECM (g's)	Percent Difference
1	0.55	0.46	-17.00
2	0.55	0.46	-15.73
3	0.52	0.45	-13.84
4	0.51	0.44	-13.84
5	0.53	0.46	-13.20
6	0.49	0.43	-12.34

error discussed above.) Analysis of the captured video showed that approximately 1 second after brake application, the tractor-trailer was established in its swerve. The video indicated that the drive wheels on the right side were slightly lifted off the ground due to the severity of the maneuver. [Figure 10](#) provides an indication of this wheel lift.

The tractor used for testing did not have limited slip differentials. The tractor had a driver-selectable differential lock, which was not selected during testing. Thus, for the purposes of the testing, the tractor had open differentials. Therefore, it is likely that the leveling/increase in velocity indicated in the ECM data was due to wheel lift during the swerve maneuver.

Once the time scale of the ECM data was corrected, an average deceleration rate during braking was calculated. This calculated rate could then be compared to the rate calculated from the skid marks. The results are shown in [Table 2](#).

As seen in [Table 2](#), the calculated deceleration rate from the ECM underestimates the deceleration rate calculated from skid marks by 12%-17%. This phenomenon is discussed in the literature [\[4\]](#), and a correction is proposed. In the current testing, the correction proposed by [\[4\]](#) reduced the difference in deceleration rate by 2-3%. While the correction places the calculated results within the error band proposed by [\[4\]](#), the lack of sensitivity of the calculations to the corrections is likely due to the change in slope of the velocity-time plots induced by the wheel lift observed during the current tests. Furthermore, one must remember that the ECM reports data only once each second, or 1/2 second given the software issues with the Caterpillar ECM. Given the coarseness of data plotting, an error of ± 0.5 seconds in the recorded time can change the calculated deceleration rate by $\pm 8-9\%$. While this still does not explain the entire difference, a combination of data recording times and the corrections postulated in [\[4\]](#) in the absence of wheel lift may lead the investigator to a more accurate determination of the deceleration rate for a tractor-trailer. This is an area that requires further study.

SUMMARY/CONCLUSIONS

The testing reported in this paper arose from some disagreement regarding the effect of trailer ABS on the marks deposited during heavy braking. Results of this test showed that trailer wheels with ABS tend to leave continuous light marks similar to the marks left by passenger tires under heavy ABS braking. The testing also indicates that with a functioning ABS, or even with a fraction of the wheels still rolling, the system allows braked wheels to generate cornering forces and to follow the path of the tractor. The testing also showed that in the absence of ABS, the wheels tended to leave heavy, dark skid marks. As expected, in the absence of ABS, the trailer tends to obey Newton's laws and proceeds in a straight line due to the inability of locked wheels to produce cornering forces. It should be noted that these results are based on a small number of tests with a single load configuration. Therefore, the results reported here should be used in a limited sense, and further testing is warranted.

As reported in the literature, using ECM data to calculate deceleration rates for tractor-trailers may underestimate the actual rate of deceleration. This is an area requiring further study to determine the cause of the differences, a reliable correction factor, and the circumstances under which the factor should be applied.

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