U.S. Department of Transportation

National Highway Traffic Safety Administration

ODI RESUME

Investigation:	EA 12-007		
Prompted by:	PE12-007		
Date Opened:	09/13/2012	**Date Closed:**	12/03/2015
Investigator:	Ric Willard	**Reviewer:**	Bruce York-B
Approver:	Frank Borris		
Subject:	MCI Drive Shaft Safety Loop Failures		

MANUFACTURER & PRODUCT INFORMATION

Manufacturer:	Motor Coach Industries
Products:	1992-2012 MCI D & E Series Buses with Steerable Tag Axle
Population:	325
Problem Description:	In the event of a drive shaft failure, the separated drive shaft is not adequately contained and can cause a loss of vehicle control.

FAILURE REPORT SUMMARY

	ODI	Manufacturer	Total
Complaints:	1	3	4
Crashes/Fires:	2	1	2**
Injury Incidents:	2	1	2**
Number of Injuries:	50	0	50
Fatality Incidents:	1	1	1**
Number of Fatalities:	2	2	2**

** Total eliminates duplicates received by ODI and manufacturer.

ACTION / SUMMARY INFORMATION

Action: This Engineering Analysis is closed. See NHTSA safety recall 14V-335.

Summary:

In the fall of 2011, network contacts made ODI aware of four (4) incidents of drive shaft failure on the subject buses involving a loss of vehicle control. Two of the incidents were relatively low speed non-crash events; and two resulted in motor coach rollovers. All four events showed signs of a common failure mode.

The incidents and crashes studied during this investigation all resulted from a series of complex events that began with the the yoke journal ears on the drive shafts fracturing. Once the drive shaft failed. it was not adequately contained by a drive shaft safety loop or structure. The spinning and unrestrained drive shaft caused severe damage to components on the steerable tag axle at the rear of the vehicle and created a forced steering condition. Once the rear of the bus was being forcibly steered by the tag axle, the driver lost control of the vehicle. These conclusions are based on the forensics evidence and testing conducted by the Vehicle Research and Test Center (VRTC). The VRTC test report is attached to this closing resume that provides details on how the test center was able to conclusively identify the defective components on the buses and demonstrate the sequence of events that caused the buses to crash.

Prior to the drive shaft failure events, there were no indications of improper maintenance or that maintenance was required that would have prevented the incidents. Additionally, the U-joints on the incident vehicles were found to be in good working condition at the time of the failure. Finally,
records of driver interviews indicated a sudden onset of the failure with no warning.

Following the VRTC testing, MCI issued recall 14V-335 involving certain model year 1993-1995 102DL3 motor coaches manufactured November 1992 to January 1995, and 2006 and 2008 D4505 motor coaches manufactured June 2005 to April 2008. The affected buses are equipped with a drive shaft with a compressed length of 30 inches or less (allowing it to escape containment if it fails), a steerable trailing tag axle equipped with a system that changes the axle caster when the vehicle is in reverse travel and no electronic stability control (ESC). Recall 14V-335 addresses the concerns of this investigation.

The ODI report cited above can be viewed at www-odi.nhtsa.dot.gov/owners/SearchNHTSAID: ODI Number 10447575.

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National Highway Traffic Safety Administration

November 2015

1992-2012 MCI D-Series Bus Driveshaft Failure

DISCLAIMER

Technical Report Documentation Page

1. Report No.
2. Government Accession No.
3. Recipient's Catalog No.
4. Title and Subtitle
1992-2012 MCI D-Series Bus Driveshaft Failure
5. Report Date
November 2015
6. Performing Organization Code
NHTSA/NVS-313
7. Author(s)

William Collins, National Highway Traffic Safety Administration
Tim Cleland, Transportation Research Center Inc.

8. Performing Organization Report No.
9. Performing Organization Name and Address

National Highway Traffic Safety Administration
Vehicle Research and Test Center
P.O. Box B-37
East Liberty, OH 43319

10. Work Unit No. (TRAIS)
11. Contract or Grant No.
12. Sponsoring Agency Name and Address

National Highway Traffic Safety Administration
1200 New Jersey Ave., S.E.
Washington, D.C. 20590

13. Type of Report and Period Covered
Final Report
14. Sponsoring Agency Code
15. Supplementary Notes

The authors thank Michael Rhoades, Rick Hughes, Jared Dowdy, and Duane Stoltzfus of the Transportation Research Center, Inc. for their testing support.

16. Abstract

This test program was performed by the National Highway Traffic Safety Administration (NHTSA) at its Vehicle Research and Test Center (VRTC) at the request of the Office of Defects Investigation (ODI). ODI requested that VRTC evaluate whether a driveshaft failure could damage the bus's steerable rear tag axle system and contribute to loss of steering control in Motor Coach Industries International (MCI) D-Series buses. Allegations of loss of control were reported to NHTSA by the fleet operations office for Greyhound Lines, Inc. Two of the alleged incidents led to crashes and one resulted in fatalities. Information gathered from the accident reports, along with retrieved parts, were used as the basis to design testing methods for determining whether a broken driveshaft damages critical tag axle steering system components.

The crashes studied in this investigation were a result of a series of events that began with the mechanical failure of the driveshafts in Americanos 60630 and the Greyhound 6352 crashes. The driveshaft failures created a chain reaction of equipment failure that ultimately caused a malfunction of key controllability components of the steerable tag axle system. These conclusions are based on the forensics evidence and testing conducted by VRTC.

Conclusions:

- The root cause of the driveshaft failure occurs as a direct result of the cast yoke journal ears fracturing.
- There were no indications of improper maintenance or that maintenance was required that would have prevented the incidents.
- Records of driver interviews indicated a sudden onset of the failure with no warning.
- A failed driveshaft will not be adequately contained by the driveshaft loop.
- The driveshaft failure can create a forced steering condition when the tie rod is deformed by impacting blows of the flailing shaft.

Summary of the Chain of Events:

- The driveshaft yoke fails resulting in the driveshaft decoupling from the transmission hub and eventually escaping the tag axle pass-through (containment) structure.
- The driveshaft impacts the tie rod causing sufficient bending to defeat the latching plates, allowing the tie rod and steering knuckles to swing.
- A forced steering of the tie rod occurs from continuous rotational impacts of the driveshaft to the latching plate clamp block on the tie rod.
- The caster position latching tongue fails from driveshaft impacts or levering and frees the axle, allowing forward rotational movement into negative caster.
- A caster change in the negative direction occurs due to axle roll from braking or being forcefully levered by the driveshaft once the latching tongue fails.

With the negative angle caster change, the steerable tag axle wheels are prevented from returning to a straight orientation and cause the rear of the bus to swing out of a straight travel direction.

17. Key Words
18. Distribution Statement
19. Security Classif. (of this report)
Unclassified
20. Security Classif. (of this page)
Unclassified
21. No. of Pages
xx
22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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1.0 INTRODUCTION

This test program was performed by the National Highway Traffic Safety Administration (NHTSA) at its Vehicle Research and Test Center (VRTC) at the request of the Office of Defects Investigation (ODI). The development and testing used both controlled vehicle dynamic and static component engineering test methods. ODI requested that VRTC evaluate whether a driveshaft failure could damage the bus's steerable rear tag axle system and contribute to loss of steering control in Motor Coach Industries International (MCI) D-Series buses. Allegations of loss of control were reported to NHTSA by the fleet operations office for Greyhound Lines, Inc. Two of the alleged incidents led to crashes and one resulted in fatalities.

This report depicts the testing completed by VRTC, with reference to accident report information and physical crash evidence. Information gathered from the accident reports, along with retrieved parts, were used as the basis to design testing methods for determining whether a broken driveshaft damages critical tag axle steering system components.

Although two of the accidents reported to NHTSA were rollover crashes which acted as the basis for testing, the scope of the report also includes additional non-crash incidents that had experienced a similar driveshaft failure mode. Testing was limited to MCI D-Series buses without antilock (ABS) brake systems or electronic stability control systems (ESC), since both rollover crashes were on buses that did not incorporate either of these features.

2.0 BACKGROUND

2.1 Steerable Tag Axle Description

A tag axle is defined as a non-driven axle that trails behind the drive axle on a vehicle chassis. The function of the tag axle is to share a portion of the vehicles weight and assist in reducing tire loading of the drive axle. Tag axles are commonly used in heavy motor vehicle applications, such as trucks and buses, and are typically used with a rear engine design chassis, such as a motor coach.

A steerable tag axle, like the MCI D-series axle, offers additional advantages over a fixed non-steering tag axle. Unlike a fixed tag axle, the steering capability helps reduce lateral tire loading of the drive axle tires as the vehicle turns, reducing wear and allowing the vehicle to make a shaper turn as it actually helps to steer the rear of the vehicle around corners. A motor coach with a steerable tag axle is shown in Figure 1 making an assisted turn, while Figure 2 shows a close up of turned tag axle wheels in reference to the drive axle wheels. All testing conducted by NHTSA was limited to the MCI D-series steerable style tag axle only.

Figure 1 - Motor Coach Shown Turning with Steerable Rear Tag Axle

Figure 2 - Steerable Rear Tag Axle with Wheels Turned

The MCI D-series tag axle steers passively by automatically releasing a tie rod at speeds below 15-20 mph and positioning the caster of the axle in either a forward or reverse caster position depending on the transmission gear selected. The tie rod is released when a pneumatically controlled pin is retracted from a latch plate attached to the tie rod. Once the tie rod is released, the wheels passively steer while the axle's caster is correctly positioned for the direction of travel. This change in caster angle is controlled by the transmission position selector for both forward and reverse movement of the bus, allowing the tag axle to assist steering effectively in either direction. As the bus accelerates to speeds above 15-20 mph in the forward direction, the tie rod is re-latched by a pneumatic locking mechanism. An MCI D-series tag axle and the specific components of the axle that will be discussed throughout the report are shown in Figure 3.

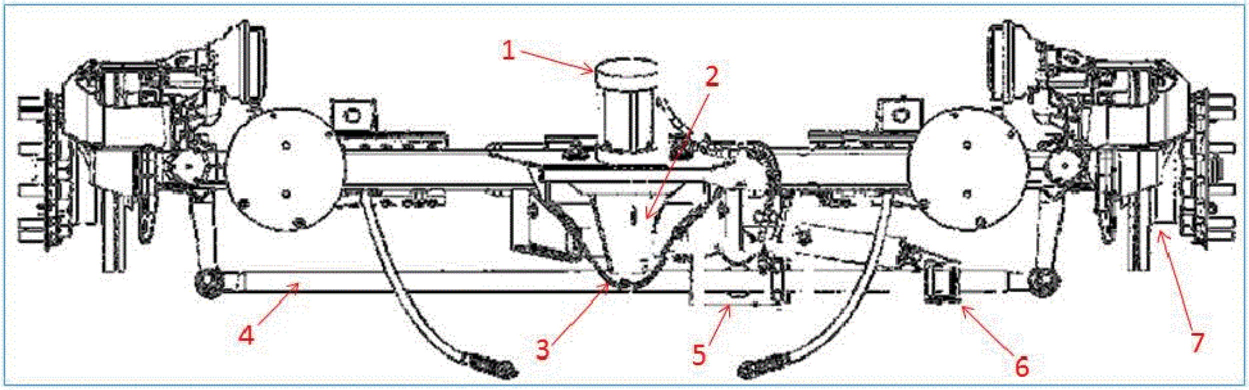

Figure 3 - Top View of MCI D-Series Steerable Tag Axle

#1 – Caster Positioning Pneumatic Cylinder
#2 – Caster Position Latching Tongue Plate
#3 – Caster Position Safety Stop Strap
#4 – Steering Tie Rod
#5 – Tie Rod Pneumatic Latch Mechanism

#6 – Tie Rod Damping Shock Assembly
#7 – Steering Knuckle

2.2 How Caster Angle Change Is Applied to the MCI D-Series Tag Axle

The caster angle identifies the forward or backward slope of a line drawn through the upper and lower steering pivot points when viewed from the side of the wheel. Caster is expressed in degrees and is measured by comparing a line running through the steering system's upper and lower pivot points to a line drawn perpendicular to the ground. Caster is considered to be positive if the line slopes towards the rear of the vehicle at the top, and negative if the line slopes towards the front.

The 6° caster change between forward and reverse travel that occurs to the MCI tag axle wheels is depicted in Figure 4. The negative caster change is used to keep the same self-centering stability between the steering knuckles when traveling in reverse and allow the tie rod to re-latch easily again in forward travel once speeds increase above 15-20 mph. This caster change creates a positive wheel trail for either direction to maintain the steering knuckle stability. The axle caster positioning cylinder adjusts the axle caster whenever the vehicle transmission changes from forward to reverse. The cylinder rolls the axle forward 6° to a negative caster position for reverse direction or returns the axle to the home position of a positive caster for forward travel direction.

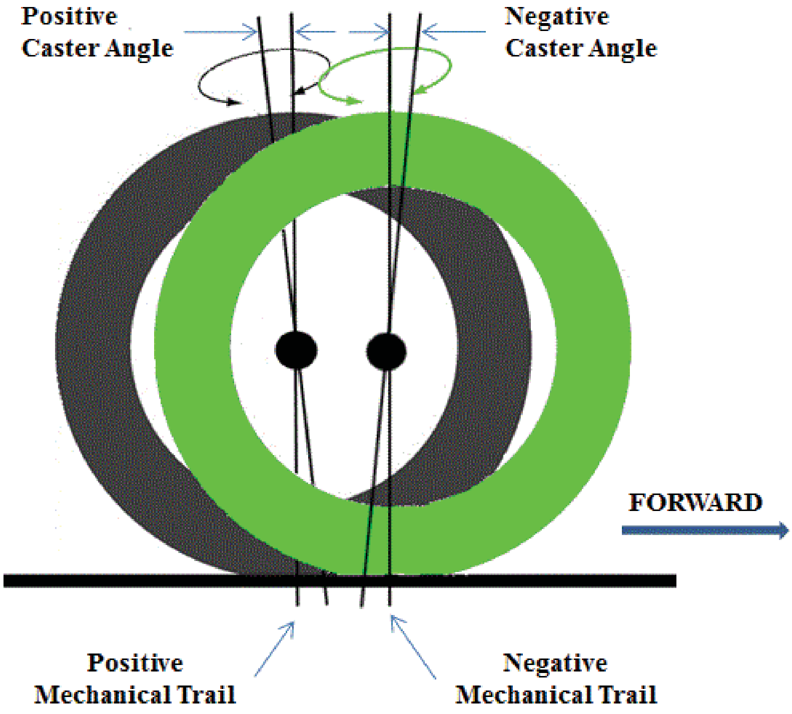

Figure 4 - Graphic Showing Caster Change from 3° Positive to 3° Negative

2.3 Prior Recall 09V-350

In September of 2009, MCI implemented a voluntary recall 09V-350[1] for certain coach models that were experiencing non-latching tie rods or for which the tie rod was latching with the wheels not in a straight ahead position. It was determined by MCI that if the tag axle does not lock at speeds above 20 mph, a loss of lateral force control of the tag axle occurs and can affect steering control of the vehicle. This condition also makes the rear of the vehicle swing further out when turning and increases the risk of striking another vehicle. The tie rod latch assembly is shown in Figure 5. The testing conducted by NHTSA indicated that a driveshaft failure is capable of damaging the tie rod latch assembly resulting in the release of the tie rod and producing a similar loss of steering control as described in recall 09V-350. A driveshaft failure can damage and defeat the tie-rod latching mechanism. This will be discussed in detail in Section 5 of the report.

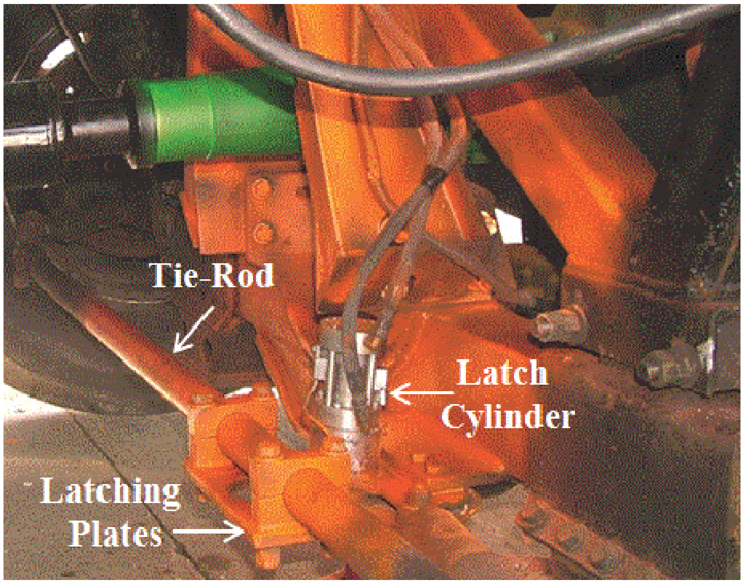

Figure 5 – Close-up of Tie-Rod Latch Assembly

2.4 Associated Failures

There were several associated incidents of alleged driveshaft failures resulting in a loss of steering control that were reported to NHTSA by Greyhound Lines, Inc. Fleet Operations. The alleged failures reported to NHTSA are shown in Table 1. Although units 6468 and 6931 were non-crash events, they were included in NHTSA’s testing and analysis since they both experienced the same common mode of driveshaft failure resulting in a loss of steering control.

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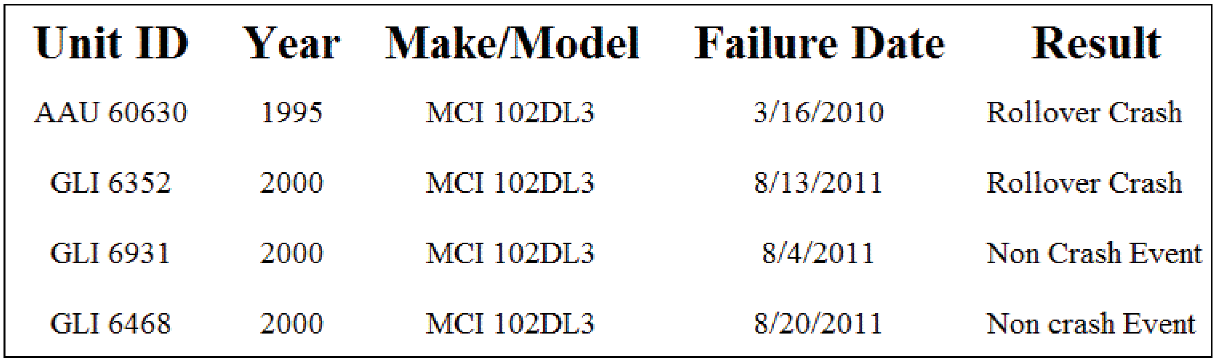
[1] NHTSA Campaign ID Number: 09V-350



Unit ID	Year	Make/Model	Failure Date	Result
AAU 60630	1995	MCI 102DL3	3/16/2010	Rollover Crash
GLI 6352	2000	MCI 102DL3	8/13/2011	Rollover Crash
GLI 6931	2000	MCI 102DL3	8/4/2011	Non Crash Event
GLI 6468	2000	MCI 102DL3	8/20/2011	Non crash Event

Table 1 - Reported Known Loss of Steering Control Failures

2.5 Information Request Response to NHTSA

As normal practice, a formal information request (IR) letter was used as part of ODI's Preliminary Evaluation (PE) procedure. Information request PE12-007[2] was issued to MCI to gather supporting information related to the alleged defect directly from the manufacturer for evaluation and analysis. The requested information returned to NHTSA from MCI contained some responses that did not agree with the preliminary findings by ODI. The main points of difference were posed as the following questions to be answered as part of the basis for the investigation.

1. Can a driveshaft escape from the tag axle pass-through assembly when detached from the transmission?
2. Can a freed driveshaft strike and damage steering components of the tag axle resulting in loss of steering control?
3. Does an unlatched tie-rod produce an unsafe driving condition?
4. Is the root cause of the universal joint failure maintenance driven?

MCI's evaluation of both accidents did not fully explain the accident report data, testimonial information, or physical evidence. It was determined by ODI that additional testing and analysis was required, so the test program described in this report was conducted at VRTC.

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[2] NHTSA Preliminary Evaluation ID Number: PE12-007

3.0 OBJECTIVE

The objective of NHTSA’s testing was to understand and demonstrate failure modes and effects a freed driveshaft would have, particularly in damaging the tag axle steering system components, while also evaluating whether these failure modes present a loss of vehicle control and unreasonable risk to safety.

4.0 TEST VEHICLE

4.1 MCI D-Series Bus Test Platform

A 1995 MCI model 102DL3 bus[3] with the D-series steerable tag axle was used as the dynamic testing unit throughout the investigation. The vehicle is shown in Figure 6 and was equipped with a 60-Series Detroit Diesel engine and an Allison HT740 transmission. This engine and transmission combination was equivalent to both subject crash vehicles, and it had the same driveshaft working length. The test vehicle did not have anti-lock brakes; nor did it feature electronic stability control. The braking devices were conventional drum air brake style, which were the same as the subject vehicles.

Figure 6- VRTC Test Vehicle D Series MCI Bus

4.2 Pre-Test Mechanical Service

Prior to testing, a mechanical inspection was conducted to ensure correct functionality of the tag axle and all other relevant mechanical components. All brake linings and drums were replaced using OEM parts, and an FVMSS 105[4] brake burnish was performed to achieve proper brake performance. Suspension airbag leaks were repaired and tires replaced as necessary. Alignment of the tag axle was also checked for the correct toe measurement of 1/16 inch, and the steering knuckle stop bolts were adjusted for 12 degrees of lateral swing for both wheels whenever the tie rod was unlatched. A bent lower radius rod and the damping shock on the tie rod were also replaced.

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[3] Vehicle Identification Number: 1M8PDMPA0RP046569

[4] CFR 49 PART 571.105-FEDERAL MOTOR VEHICLE SAFETY STANDARD NO. 105; HYDRULIC and ELECTRIC BRAKE SYSTEMS.

4.3 Vehicle Ballasting

The test vehicle was ballasted to replicate full occupancy weight. Water-filled ballast dummies were positioned in each seat as shown in Figure 7. Additional steel plate weights were placed in the lower baggage compartments, adjusting the total weight to the approximate GVWR of 44,400 lbs. Individual axles were each ballasted to within their load ratings, and tire pressures were maintained at the maximum rated pressure of 120 psi.

Figure 7- Water Dummy Ballasted Seats

4.4 Auxiliary Controls

An external pneumatic system was constructed in the rear lower storage compartment that used compressed nitrogen to act independently from the bus air system. This independent system allowed the tag axle pneumatic components to be overridden so they could be manipulated into normal or failed conditions during testing. The external pneumatic system and solenoid control valves are shown in Figure 8. Figures 9 and 10 show the caster position and tie rod latch cylinders of the tag axle that were being controlled.

Figure 8- External Pneumatic Control System

Figure 9- Auxiliary Controlled Caster Position Cylinder

Figure 10- Auxiliary Controlled Tie Rod Latching Cylinder

4.4.1 Pneumatic Systems Controller

Electrical solenoid control valves, shown in Figure 11, were used to control the state of the tag axle caster position cylinder, tie rod latch cylinder, and other additional specialized pneumatic devices. The controller switch boxes are also shown in Figure 12.

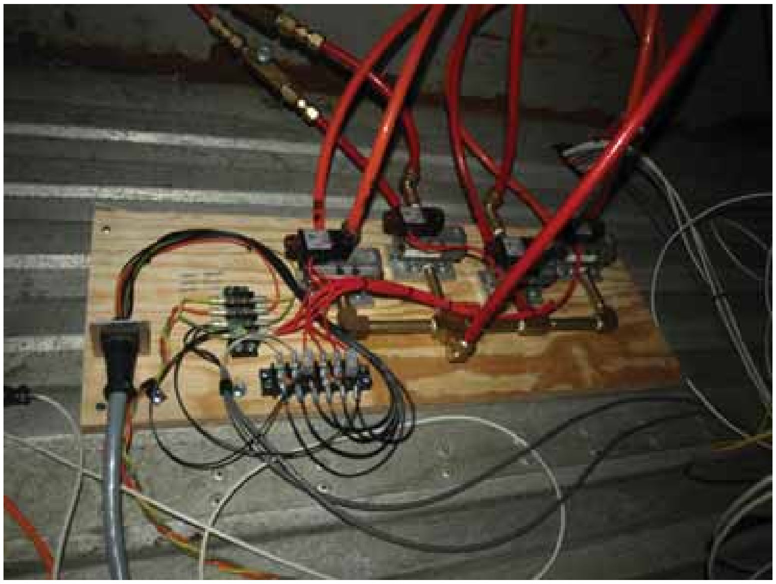

Figure 11- Pneumatic Solenoid Control Valves

Figure 12- Pneumatic Valve Control Switch Boxes

4.4.2 Tie Rod Push Cylinders

Large bore pneumatic cylinders, shown in Figure 13, were mounted horizontally to the tag axle structure directly above the tie rod. Push blocks were clamped to the tie rod allowing the cylinder to either nudge or push and hold the tag axle steering knuckles in a turned position while driving. These were used to replicate a forced steered condition that might be produced by lateral and rotational striking forces from a flailing driveshaft as it strikes the tie rod latch cylinder mounting block, resulting in the wheels being pushed into a steered position.

Figure 13- Tie Rod Push Cylinder

4.4.3 Caster Latch Defeat Cylinder

A small pneumatic cylinder was mounted vertically so that when enabled, it would lift the caster position latching tongue upward to defeat the latch arm assembly. This condition was used to test whether the caster positioning cylinder pullback force to keep the axle in the home position was greater than the torque produced by the axle's wheel brakes. It also replicated the condition where the tongue may bounce from impact shock loads. Since it is mounted with rubber bushings, the latch can be defeated by bouncing as well. The cylinder is shown in Figure 14 mounted directly below the front edge of the latch tongue.

Figure 14- Caster Latch Tongue Lift Cylinder

4.4.4 Quick Change Toe-in Tie Rod

Another specialized testing device constructed was a quick position change tie rod that would produce a toe-in condition of the right rear tag axle wheel under dynamic driving conditions. The tie rod was sectioned and a large bore pneumatic cylinder was inserted, then coupled to a high flow high pressure air source. When the cylinder was extended, the tie rod was at the correct working length. When the cylinder was retracted very rapidly, the tie rod shortened in length equivalent to the length of measured crash parts. The installed adjustable tie–rod can be seen installed in Figure 15. Figure 16 shows the stop adjustable mechanical collar limiting the amount of shortening effect to the overall length.

Figure 15- Fast Action Pneumatic Toe-in Tie Rod Installed

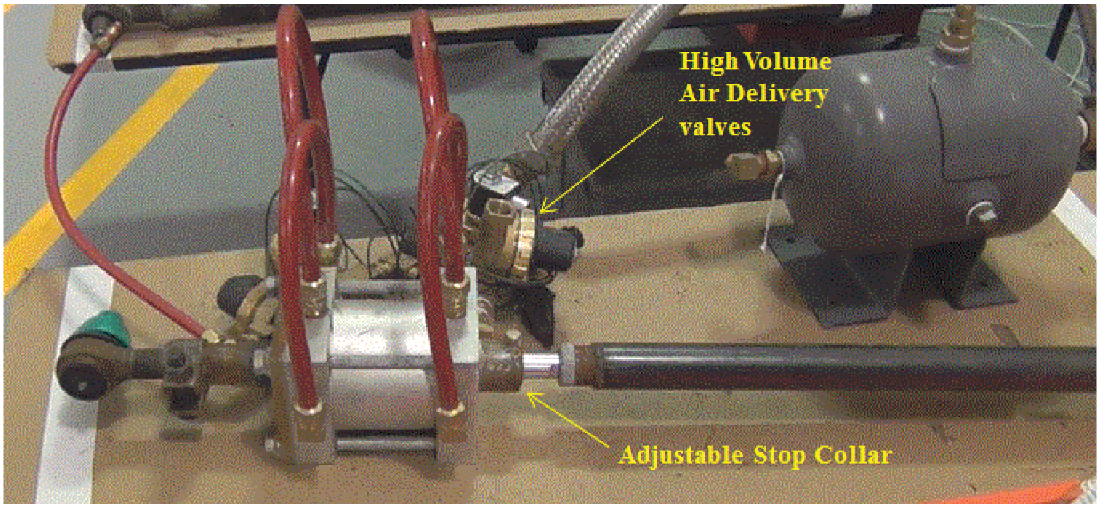

Figure 16- Quick Change Toe-in Tie Rod Detail View

4.5 Instrumentation Equipment

A 16 channel data acquisition package, shown in Figure 17, was installed to record data produced from multiple transducers and instrumentation devices used to measure critical chassis suspension components, functionality of mechanical systems, and vehicle stability under testing conditions. Common industry instruments were installed throughout the vehicle including accelerometers, yaw rate sensor, and ultrasonic transducers to measure vehicle stability and roll angle. Linear potentiometers and load cells were used to record steering angles of axles, tag axle caster position and forces of specific components such as brake pedal force.

A Global Positioning System (GPS) engine with a 100 Hz update rate and Doppler shift was used to measure vehicle speed and heading during testing. DC voltage tachometers were installed on the drive and tag axle wheels to detect brake lockup and wheel slide. Other monitored items included the brake air pressure, caster position and tie rod latch, the operating state of the specialized devices such as the toe-in tie rod, forced knuckle push cylinders, and the latching tongue defeat cylinder.

Figure 17- Instrumentation Data Acquisition Package

4.6 Video Equipment

Digital high definition cameras, shown in Figure 18, were mounted in strategic locations on the test vehicle to record specific components and events during dynamic testing. Video cameras used during this test program included nine video cameras mounted on-board the vehicle, off-board stationary video cameras, and a mobile camera mounted on a separate vehicle that followed the bus.

Figure 18- Miniature HD Video Cameras Used Throughout Testing

A view from one of the stationary cameras (Figure 19) shows the video chase-vehicle in pursuit while documenting the rear attitude of the bus tire positions and tire markings during a dynamic maneuver.

Figure 19- Video Chase Vehicle in Progress during a Test Run

4.7 Outriggers

As an additional safety precaution due to the risk of rollover, the test vehicle was fitted with anti-rollover outriggers. Figure 20 shows the riggers being load tested to a safety factor that can lift the wheels off the ground.

Figure 20- Vehicle Outriggers Undergoing Integrity Load Test

Figure 21- Extended Outriggers during a Test Maneuver

Figure 21 shows outriggers extended while the vehicle performs dynamic testing to determine vehicle stability. The vehicle ballasting was adjusted to maintain the correct GVWR and axle load ratings while maintaining the original approximate CG location.

5.0 RECONSTRUCTION

As part of NHTSA's investigation, an in-depth analysis including reconstruction techniques were applied to both subject crash incident vehicles. A variety of sources were used to collect both accident documentation and actual evidence parts for study.

5.1 Americanos Bus 60630 Crash

In March of 2010, Americanos bus 60630 was traveling southbound on Interstate Highway- 37 near Campbellton Texas. The driver reported hearing a loud noise from underneath the bus and the vehicle yawed to the right. The driver alleged that she applied braking and corrective steering unsuccessfully to regain control as the vehicle then went into a left sideways skid, crossed both lanes, and slid into the highway median. The vehicle then rolled one-quarter turn onto the right-hand side of the bus coming to rest in the center of the dividing median, as shown in Figure 22[5], resulting in two fatalities and numerous injuries. The vehicle was traveling approximately 65 mph at the time of the crash and was transporting 45 occupants, including the driver.

Figure 22- Americanos Bus 60630 Crash Scene Press Photo

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[5] USA Today, via Associated Press
Updated 03/17/2010

5.1.1 Accident Report and Documentation Analysis

Accident reports reviewed by NHTSA included the Texas Peace Officer's Crash Report Form (CR-3 1/12010) and the Texas Highway Patrol Division Major Crash Investigation Report (IH-37 10-50). Both reports were completed by the Texas State Highway Patrol with assistance from the State Department of Public Safety (DPS) Crash Reconstruction Team. The investigation report includes a detailed scaled crash survey map of the roadway scene depicting all tire markings and locations of evidence items immediately recovered. A refined version of the survey map was created by ODI, which focused on understanding the unique tire markings produced and how they correlated to the reported driver's actions and vehicle dynamics during the progression of the crash event. The refined map created using the survey recorded coordinates from the DPS report is shown in Figure 23. The mapping included the projected path of the bus and identified individual markings made by specific wheels.

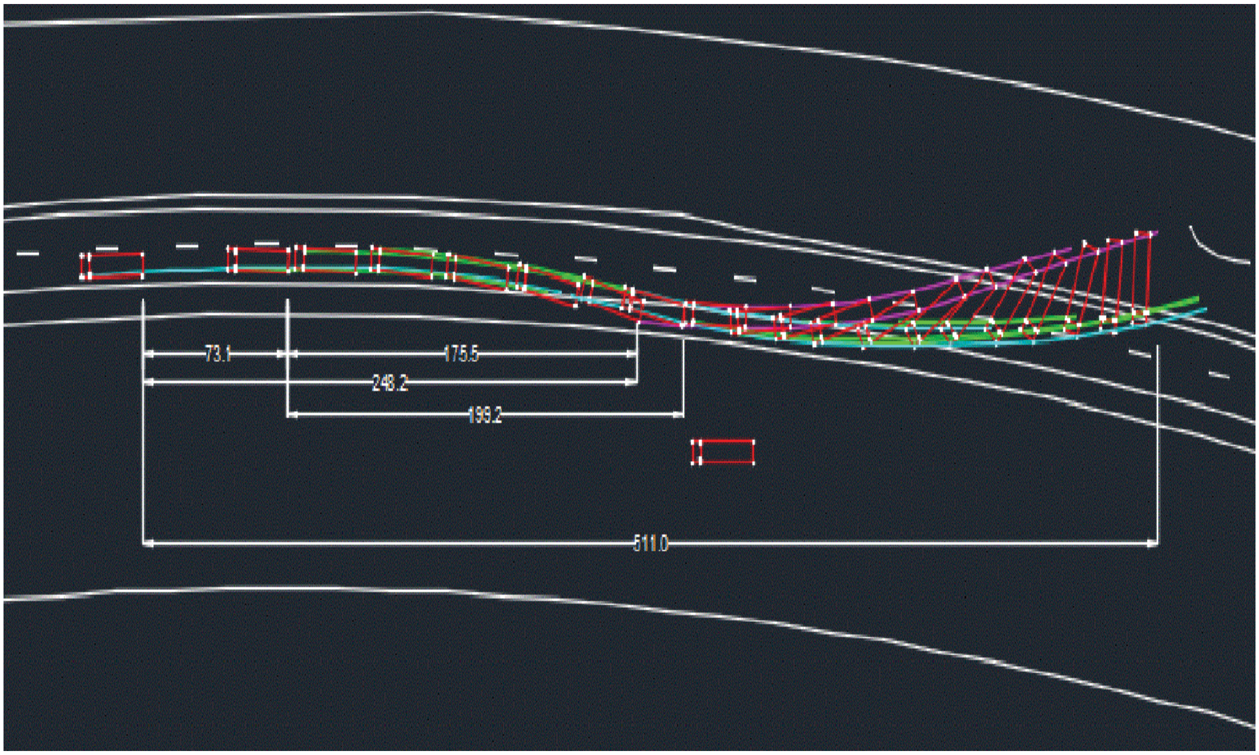

Figure 23- Engineering Refined Crash Site Survey Map

5.1.2 Tire Markings at Scene

A crash scene photo shown in Figure 24[6] was taken by the DPS reconstruction team. The image illustrates the complexity of the tire markings. The accident report indicated that all tires were in good condition and there were no air leaks in the vehicle brake system.

Figure 24- Crash Scene Tire Markings

The survey mapping of the crash site showed a unique tire mark that was vital to understanding the first moments of the event. Additional crash scene photos taken by the reconstruction team showed a single tire marking being made in the outer right-hand wheel path for approximately the first 100 feet of the event before lock and slide tire marks from the drive axle duals were present. Figure 25[7] shows the tire mark looking back northbound at the initiation point of the event. Figure 26[8] shows the tire mark looking southbound in the direction of travel of the accident.

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[6] Texas DPS State Crash Reconstruction Team
Taken 03/16/2010 Dscn0590

[7] Texas DPS State Crash Reconstruction Team
Taken 03/17/2010 ARA 30011-034

[8] Texas DPS State Crash Reconstruction Team
Taken 03/17/2010 ARA 3011-051

P000159

Figure 25- Northbound View Single Tire Marking

P000176

Figure 26- Southbound View Single Tire Marking

This photo in Figure 27[9], taken by the DPS team, illustrates that the rear tag axle tires are drawn into a toe-in condition that was hypothesized and later proven to be capable of producing the single tire mark evident at the initiation of the marks leading to crash site. The first strikes to the tie rod from the disconnected rotating driveshaft bent the tie rod inward and pulled (in tension) the leading edge of the wheels towards each other. In a normal toe-in condition, the directional forces created by each tire will balance out to a relatively neutral state. However, this bus design incorporates a latching mechanism on the tie rod near the left wheel that prevents it from toeing-in and causes the right wheel to turn inward with approximately twice the angle. The right wheel remained toed-in until subsequent driveshaft strikes overcame the latching plates, which effectively rendered the rear tag axle free to swing from uncontrolled inputs. Reproductions of the single tire marking were later reproduced by VRTC using the fabricated pneumatic quick change toe-in tie rod that is shown in Section 4 of this report.

Figure 27- Americanos 60630 Crash Scene Bent Tie Rod

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[9] Texas DPS Sate Crash Reconstruction Team
Taken 03/17/2010 Dscn0581

5.1.3 Accident Site Roadway Conditions

The condition of the roadway pavement at the crash site was also evaluated by NHTSA using photos from the DPS reconstruction team to determine if it too was a contributing factor to the accident. The images showed the pavement had deterioration, some slight rutting, and polishing. ODI made a formal request to the Texas Department of Transportation Pavement Management Information System (PMIS) to provide skid resistance (SN) data collected by the Texas State DOT at the referenced mile marker of the crash on Interstate Highway 37. The report summary provided to NHTSA by PMIS showed a lower skid resistance was measured at the specified mile marker than at the same bituminous asphalt pavement a few miles away.

The conclusion of ODI, based on the Texas DPS scene documentation and the report summary provided by PMIS, was that because the pavement was wet at the time of the accident, the lower than typical SN could result in wheel lockup of the drive axle tires under less than full braking force. A lower coefficient of friction condition would also reduce braking efficiency to some degree. It was found that certain mechanical failure conditions of the tag axle can still steer the back end of the bus with some level of authority if lateral stability forces being produced by the drive wheel tandems are diminished, even on high SN surfaces that were tested at VRTC.

5.1.4 Post-Crash Vehicle Inspection

The Americanos bus 60630 was inspected by NHTSA at a Greyhound maintenance facility to view crash damage and document forensic evidence. The bus is shown in Figure 28 parked over an inspection pit. The bus had remained in the original condition from the crash, except the damaged tag axle tie rod was straightened to transport the vehicle to the facilities.

Figure 28- Americanos 60630 at Inspection Facilities

The initial tag axle inspection showed damage to multiple areas of the inner structure where the driveshaft passes through, and it revealed considerable impact and bending damage to the caster arms and latching tongue assembly, as shown in Figures 29 and 30. The bent latching tongue clevis in Figure 30 and the witness marks on the safety catch hoop indicate the axle rolled forward into a reversed caster position while in forward travel.

Figure 29- Americanos 60630 Impact Damage to Tag Axle Caster Arms

Figure 30- Americanos 60630 Bent Caster Clevis and Witness Marks on Safety Catch Hoop

The driveshaft was found to have a fractured bearing journal ear, shown in Figure 31, and it was matched to an evidence piece found on the roadway towards the beginning of the tire markings at the crash scene, indicating that this component failed at some point prior to the crash.

Figure 31- Americanos 60630 Driveshaft Fractured Piece Mate

The telescoping driveshaft was also found in an over-compressed state, shown in Figure 32. It was determined the over-compression between the two telescoping components occurred as the end of the driveshaft wedged against the front face of the main axle beam. The witness marks can be seen in Figure 33 and show deep gouge marks and displacement of metal as the rotating end of the shaft wedged against the face of the main axle beam as it escaped.

Figure 32- Americanos 60630 Over-Compressed Driveshaft

Figure 33- Americanos 60630 Driveshaft Escape Gouging Marks

5.1.5 Additional Americanos 60630 Evidence Parts Analysis Performed

At VRTC's request, the complete tag axle was removed from the Americanos bus 60630 and sent to VRTC for closer examination of impact damage and quantifying the loss of mechanical functionality caused by the damage. Figure 34 shows the axle on a test stand after removal from the bus. The damage to the axle components was compared to other subject evidence parts for commonalities.

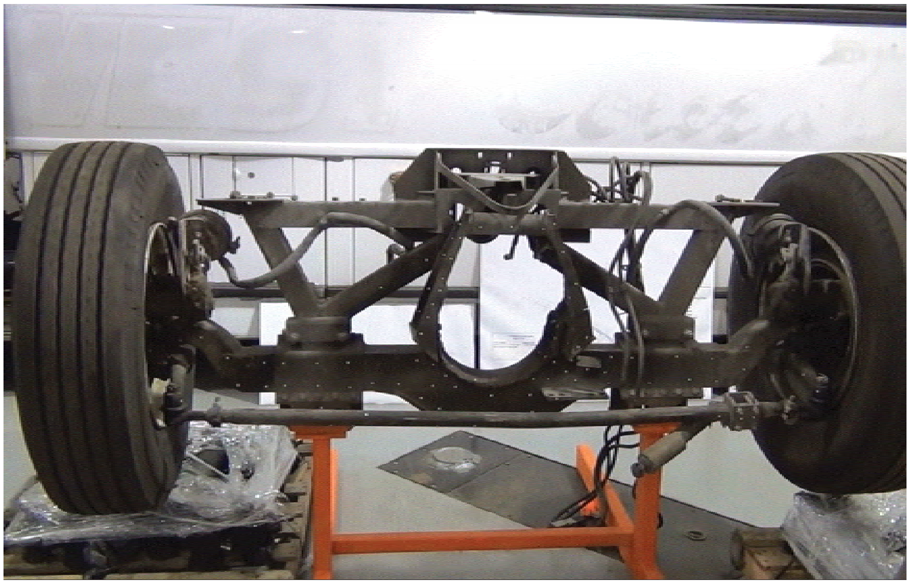

Figure 34- Americanos 60630 Tag Axle Test Stand

5.2 Greyhound Bus 6352 Crash

The Crash of Greyhound bus 6352 occurred in August of 2011 while the vehicle was traveling westbound in the left hand lane of the I-76 PA Turnpike, near Bowmansville Pennsylvania. The vehicle was traveling approximately 65 mph in a right hand curve when the bus suddenly pulled to the left, and it proceeded to strike and then ride along the concrete Jersey barrier that divides the center median. The driver stated that he applied braking and continuous right-hand corrective steering in an attempt to get the bus off of the barrier as it rode against the concrete wall, flattening the left outside drive axle tire. The vehicle then suddenly reacted sharply to the corrective steering and veered back uncontrollably to the right, crossed the right-hand lane, and exited the roadway. The bus traveled upwards on an earthen embankment adjacent to the shoulder, rolled over onto its left side, then back onto the roadway. The bus continued sliding on its side along the roadway, coming to rest across both lanes, as shown in Figure 35[10]. The crash resulted in multiple injuries sustained to several of the passengers.

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[10] USA Today, via Associated Press
Updated 08/13/2011

Figure 35- Greyhound Bus 6352 Crash Scene Press Photo

5.2.1 Accident Report and Documentation Analysis

The accident documentation reviewed by NHTSA included two crash reports provided by the Pennsylvania State Highway Patrol. The reports reviewed were the Pennsylvania Law Enforcement Crash- Public Information Release Report and the Commonwealth of Pennsylvania Police Crash Reporting Form. Both reports were completed by the Pennsylvania State Police. The narratives and witness accounts documented in the reports by the PA State Police shared similarities to the Americanos 60630 crash. Both crashes were a loss of driveshaft event on steerable tag axle MCI buses, and they both had reported uncontrolled yawing before crashing. Although the roadway conditions and crash scenarios were dissimilar, the similarities found between the two crashes were sufficient for ODI to warrant further investigation through inspection and retrieval of evidence parts for analysis. The crash of Greyhound 6352 was now included as a second confirmed accident associated with NHTSA's overall investigation.

5.2.2 Post-Crash Evidence Inspection

NHTSA was able to conduct an inspection of Greyhound 6352 at a fleet service facility to document crash damage and collect forensic evidence items in support of the investigation. The bus had been salvaged with both the engine and transmission removed, revealing the tag axle structure. The vehicle is shown in Figure 36 parked in a salvage lot at the facility. The bus still had the crash scene tires mounted on both the front and rear drive axles. The tag axle tires had been removed, but the damaged axle assembly remained intact.

Figure 36- Greyhound 6352 at Inspection Facilities

The inspection revealed the bus tag axle tie rod displayed the same tension bent signature with impact marks and a damaged latching mechanism, shown in Figure 37. Damage patterns were substantially similar, particularly with the pneumatic latching cylinder and the steel latching plates that were levered into failure as the tie rod was being bent.

Figure 37- Greyhound 6352 Impact Damaged Tie Rod and Latch

Some of the impact mark signatures and resulting damage to the tag axle caster arms and inner structure of the pass-through can be seen in Figure 38. These witness markings and damage were comparable to what was found on the Americanos 60630 crash evidence.

Figure 38- Greyhound 6352 Impact Damage to Tag Axle Caster Arms

Metal gouging and displacement markings, shown in Figure 39, show the exiting path of the flailing driveshaft at the mouth of the pass-through directly above the tie rod. This type of damaged was typical in comparison to the Americanos 60630 tag axle structure. Witness marks on the front face of the main axle beam indicated the driveshaft wedged against the face and over compressing the driveshaft tubes, similar to the Americanos 60603 crash.

Figure 39- Greyhound 6352 Impact Damage as Driveshaft Escaped Pass-Through

An image of the bus's deflated left outside drive dual tire can be seen in Figure 40. Note the minimal body damage on the left hand-hand side of the bus, with no side lateral distortion of the rear axles. This contradicted speculation that the tag axle was pushed laterally and caused the v-shaped bend in tie rod. Rather, the outer left drive axle wheel and tire assembly would have been the contacting point at the rear of the bus on the barrier because it extends beyond the tag wheel and tire assembly; this hypothesis is supported by the deflation of the drive axle tire. With the left drive wheel deflated, more load and therefore more controlling force would be transferred to the now free-steering tag axle when the tie rod was released.

Figure 40- Greyhound 6352 Deflated Outside Drive Tire Damage

The tie rod of Greyhound 6352 was retrieved for a preliminary inspection of the impact marks and how they would characterize to the driveshaft. Again the tie rod was found to be bent in tension. Based on the witness marks, it appeared to be most likely that the tension bending of the tie rod was caused by the driveshaft impacting. The impact damage to the tie rod was examined under a high magnification digital video microscope. The radius of the impact was measured for comparison to the driveshaft tube diameter using the microscopes dimensioning software shown in Figure 41.

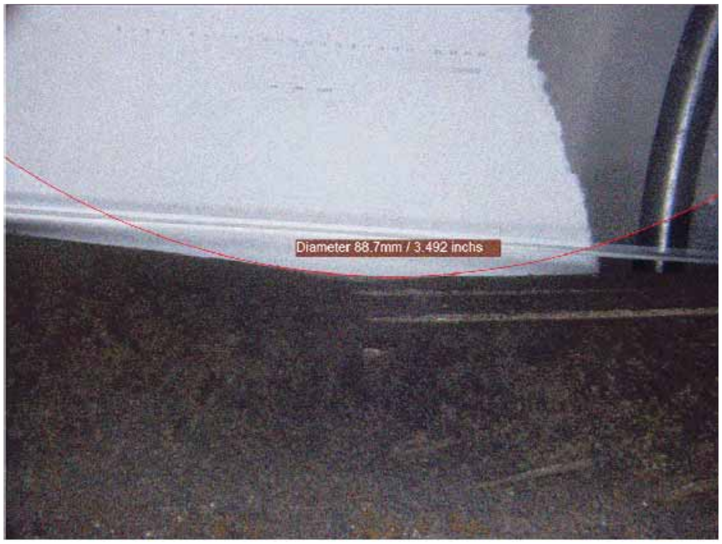


Figure 41- Greyhound 6352 Tie Rod Impact Radius Measurement

A clay impression of the tie rod impact was created and shows a distinct pattern of serration marks when viewed under the microscope. The impression is shown in Figure 42 under magnification. Note the repeated spacing of the ridges and the shallow furrowing captured by the clay impression.

Figure 42- Greyhound 6352 Tie Rod Impact Clay Impression

A clay impression of an exemplar driveshaft was compared to the impression taken from the Greyhound 6352 tie rod. The impression shown in Figure 43 exhibits a similarly distinct pattern to that of the tie rod. This similar pattern of the impressions, combined with the radius of the impact that matched the driveshaft tube diameter, demonstrated sufficient evidence that the damage to the tie rod was caused by a driveshaft.

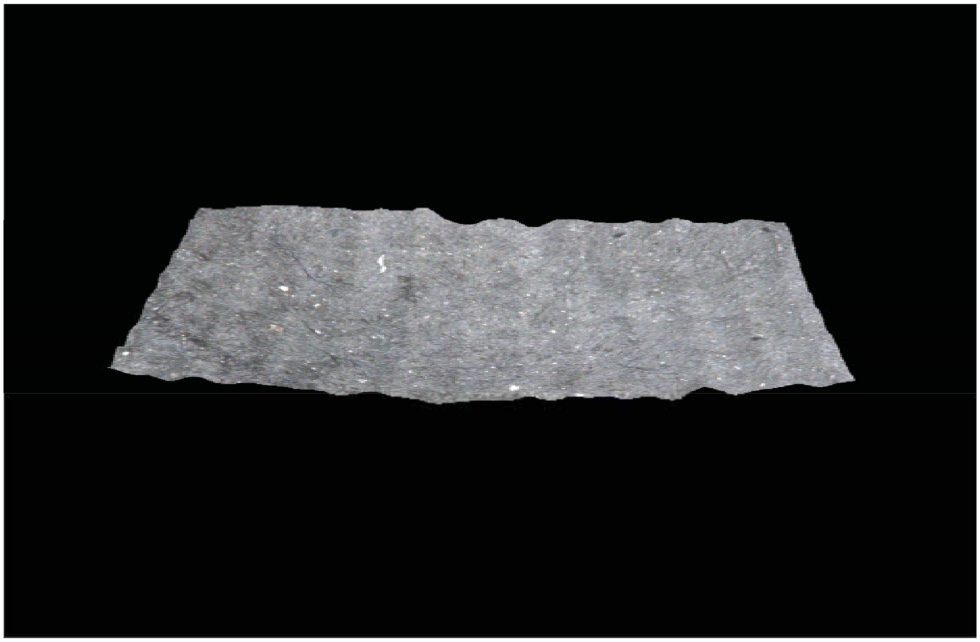


Figure 43- Exemplar Driveshaft Clay Impression

At VRTC's request, the entire tag axle assembly and related evidence parts were removed from the bus and sent to VRTC for further reconstruction and analysis. This axle was also evaluated for loss of mechanical functionality due to damage and quantifying failure modes and conditions. An in-depth comparison between the Greyhound 6352 and the Americanos 60630 tag axle damage was performed.

5.2.3 Reassembly of Greyhound 6352 Crash Evidence Parts

Evidence parts retrieved from the Greyhound 6352 crash were reassembled into a working test stand. The complete tag axle assembly with tie rod was mounted vertically, and a drive axle hub assembly was positioned on the fixture allowing the driveshaft to be connected at the hub and remain free to rotate within the tag axle structure. The fixture can be seen in Figure 44 showing the escaped driveshaft at the impact point on the tie rod.

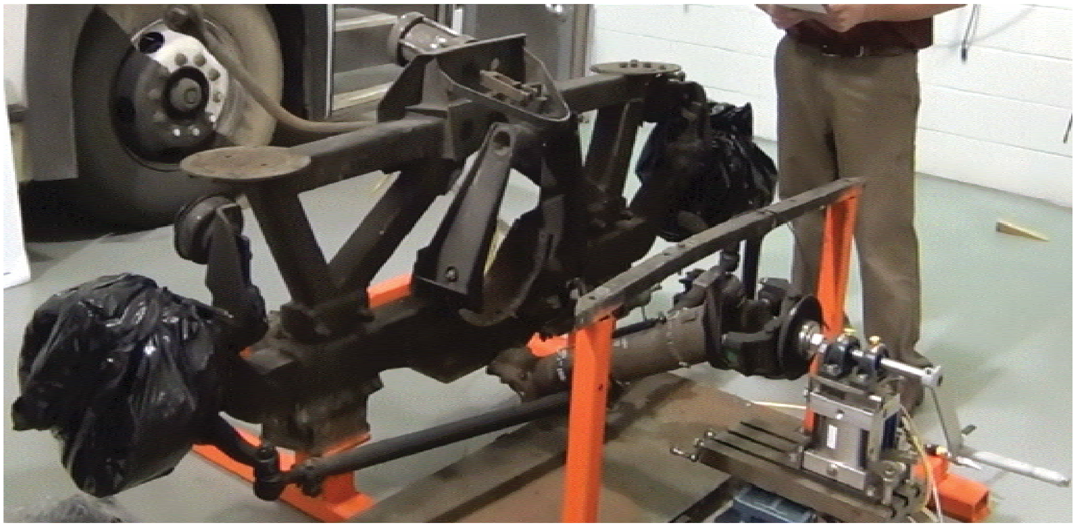


Figure 44- Greyhound 6352 Reassembled Tag Axle Test Fixture

The geometry of all reassembled evidence parts matched the exact locations and placement of the tag axle and drive line components when they were installed on the Greyhound bus 6352. Instrumentation was incorporated to digitally measure the driveshaft telescoping length as it was moved to any location on the fixture. The fixture also had the capability to actuate the pneumatic caster mechanism and induce measurable incremental movement on the drive axle hub assembly, representing suspension trailing link bushing compliance and wear.

The fixture shows the driveshaft can escape from the pass-through opening of the axle, as seen in Figure 45. The image also shows the impact damage to the tie rod latching cylinder base and latch plate clamp block. The driveshaft matched the gouging marks on the lip and face of the axle beam caused as the shaft escaped the mouth of the pass-through.

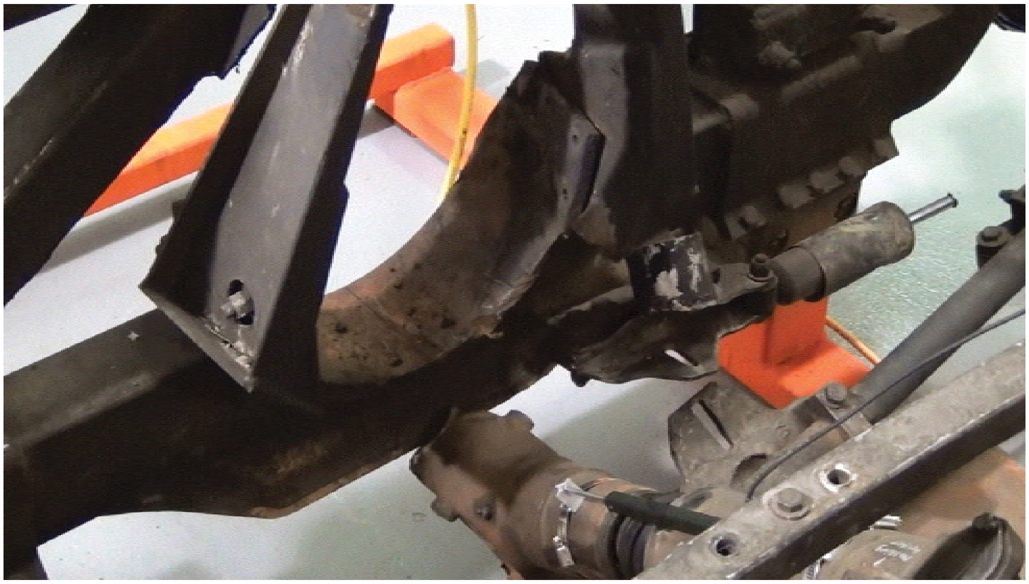


Figure 45- Greyhound 6352 Escaped Driveshaft on Test Fixture

5.3 Evaluation of Bus Components

5.3.1 Forensic Evidence of Buses 6468 and 6934 Non-Crash Events

Additional forensic evidence parts were collected by NHTSA from non-crash events involving Greyhound buses 6468 and 6934. Both events were lower speed non-crash incidents. The parts retrieved included the failed driveshaft and mating transmission hub from bus 6468 and the transmission hub from bus 6934. These evidence parts were used to assist in identifying the root cause of the driveshaft failure through analysis that revealed more commonalities among evidence collected from all four reported events. These additional evidence parts revealed a true forensic understanding of the mechanical defectiveness that triggered the failure event of the driveshaft. This identification of the root cause failure also allowed NHTSA to understand the level of detectability of the defect.

The transmission hub from Greyhound 6934 showed evidence that the U-joint retaining strap bolts were struck and sheared by the broken end of the driveshaft shown in Figure 46. Impact marks are present on the hub face with all threaded holes showing no sign of failure. The same evidence is present on the transmission hub from Greyhound 6468 shown in Figure 47. The driveshaft examined from bus 6468, shown in Figure 48, confirmed fracturing of the cast bearing journal ears on the driveshaft yoke, which produced the release mechanism for the U-joint. The same signature fracturing pattern of cast journal ears was present on both driveshafts of the Americanos 60630 and the Greyhound 6352 crash buses.

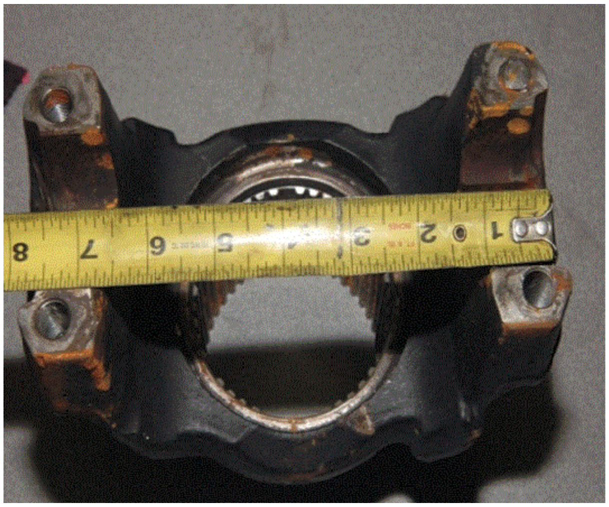


Figure 46- Greyhound 6934 Transmission Hub Damage

Figure 47- Greyhound 6468 Transmission Hub Damage

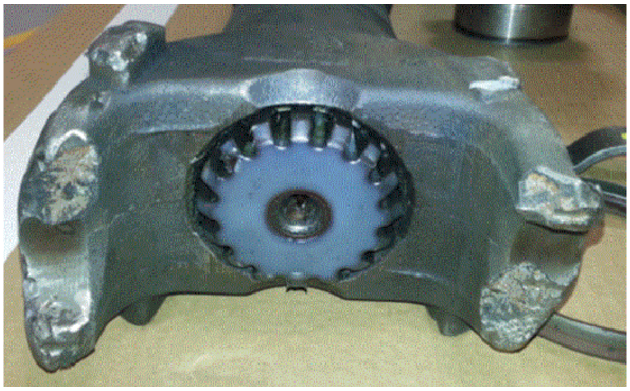


Figure 48- Greyhound 6468 Fractured Cast Journal Ear

5.3.2 Characterization of Driveshafts

Driveshafts were examined from three of the reported incidents. The evidence driveshafts used for forensic analysis were from the Americanos 60630, Greyhound 6352, and Greyhound 6468 buses, all of which experienced the same type of coupling failure at the transmission hub. The driveshafts all showed an over-compressed state of the tube splines, column fracturing of the tubes, and at least one fractured ear on the bearing journals, shown in Figure 49.


Americanos 60630 Driveshaft

Greyhound 6352 Driveshaft

Greyhound 6468 Driveshaft

Figure 49- Failed Driveshaft Evidence Comparison

Measurements were taken on evidence and exemplar parts to determine whether a driveshaft can escape the tag axle pass-through. These measurements were compared to the manufacturer's specifications. The measurements reflect the shortest compressive lengths of the driveshafts. These measurements were used to establish overall lengths and clearances at the tag axle pass-through. Figure 50 shows each driveshaft's dimensions and images of the column fracturing caused by over-compression, which further reduced the overall length. The measurements were compiled into a table that showed the interference and length inconsistencies between actual measured parts and the manufacturer provided specification drawings. The table is in Figure 51, and measurements are listed from all three collected driveshafts and an exemplar driveshaft from the VRTC test vehicle.

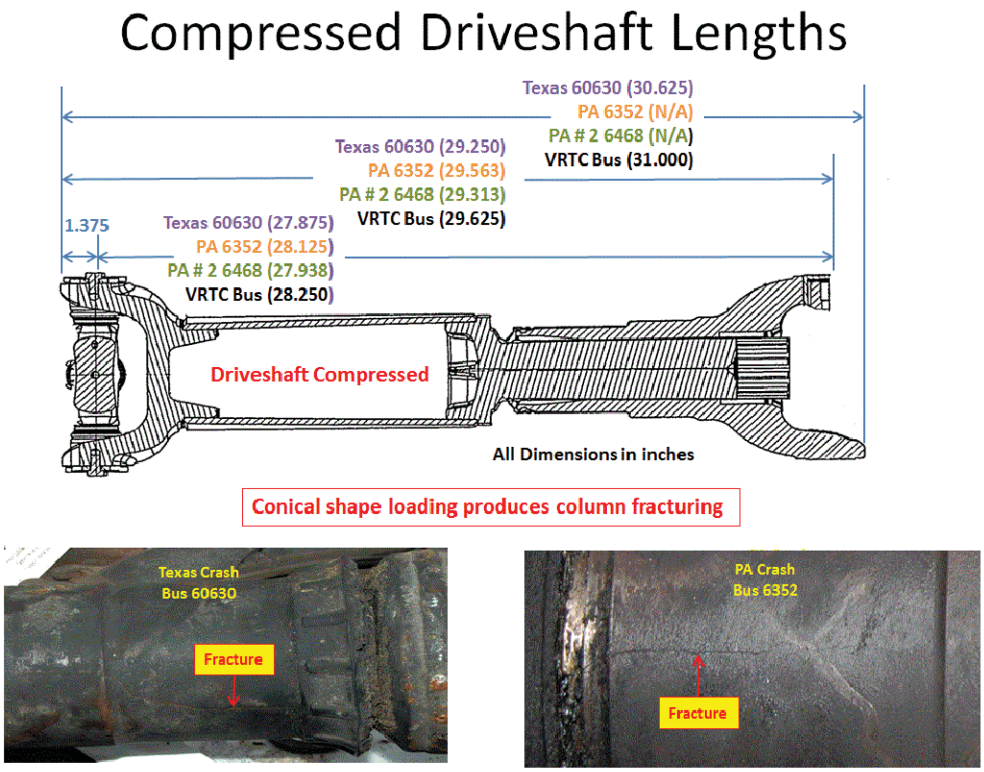
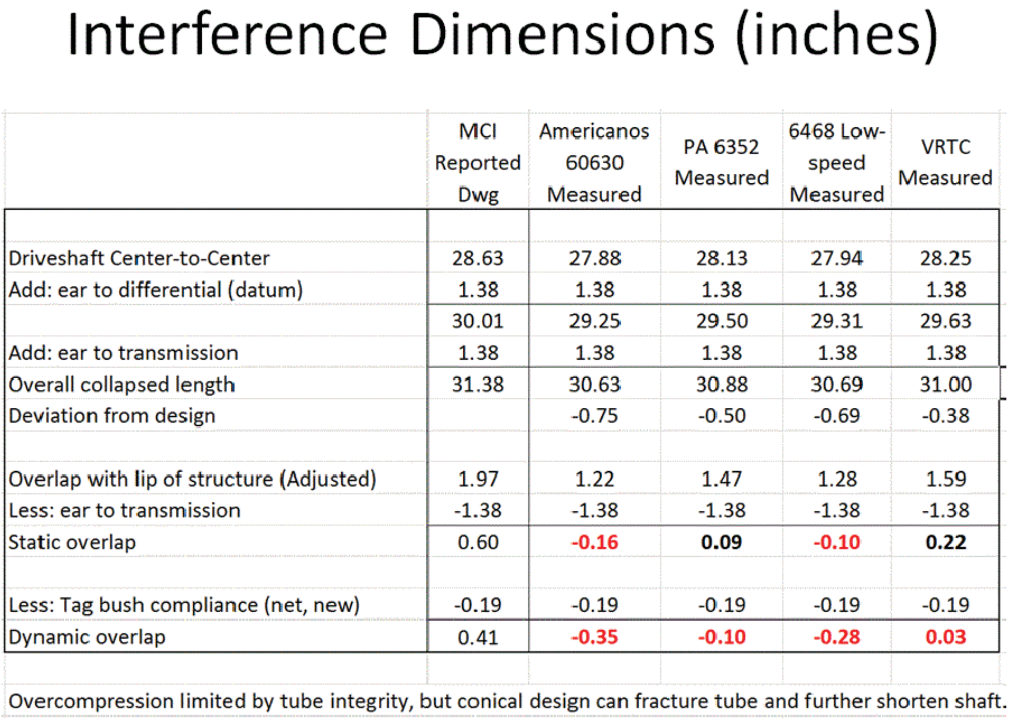


Figure 50- Compressed Driveshaft Dimensions



Interference Dimensions (inches)

	MCI Reported Dwg	Americanos 60630 Measured	PA 6352 Measured	6468 Low-speed Measured	VRTC Measured
Driveshaft Center-to-Center	28.63	27.88	28.13	27.94	28.25
Add: ear to differential (datum)	1.38	1.38	1.38	1.38	1.38
	30.01	29.25	29.50	29.31	29.63
Add: ear to transmission	1.38	1.38	1.38	1.38	1.38
Overall collapsed length	31.38	30.63	30.88	30.69	31.00
Deviation from design		-0.75	-0.50	-0.69	-0.38
Overlap with lip of structure (Adjusted)	1.97	1.22	1.47	1.28	1.59
Less: ear to transmission	-1.38	-1.38	-1.38	-1.38	-1.38
Static overlap	0.60	**-0.16**	**0.09**	**-0.10**	**0.22**
Less: Tag bush compliance (net, new)	-0.19	-0.19	-0.19	-0.19	-0.19
Dynamic overlap	0.41	**-0.35**	**-0.10**	**-0.28**	**0.03**

Overcompression limited by tube integrity, but conical design can fracture tube and further shorten shaft.

Figure 51- Driveshaft Interference Dimensions

The driveshafts also revealed that the remaining U-joint on the drive axle end of the shaft was in good working condition with little or no visible wear. The remaining bearings gave good representation of the condition of the driveshaft U-joints at the time of the failure. This evidence further supported that the root cause of the failure was the fracturing of the cast journal ear rather than a bearing failure that might have been caused by wear or lack of maintenance. The U-joint also showed distortion of the journal bearing cap retainer plates, shown in Figures 52 and 53, while grease was still present in the bearing. The distortion indicates a mechanical overload levering of the joint that occurred as the freed end of the driveshaft wedged against the tag axle face as it escaped the pass-through opening. This is likely when over-compression of the driveshaft occurred.

Figure 52- Greyhound 6352 Drive Axle U-Joint Overload

Figure 53- Greyhound 6352 Deformed Bearing Retainer Plate

5.3.3 Characterization of Tie Rods

The tag axle tie rods from both crashes have a unique similar V-shaped bend on the right-hand side of the latching plate clamp block. This common V-shaped, signature bend is shown on the Americanos bus 60630 in Figure 54 and on the Greyhound bus 6352 tie rod in Figure 55.

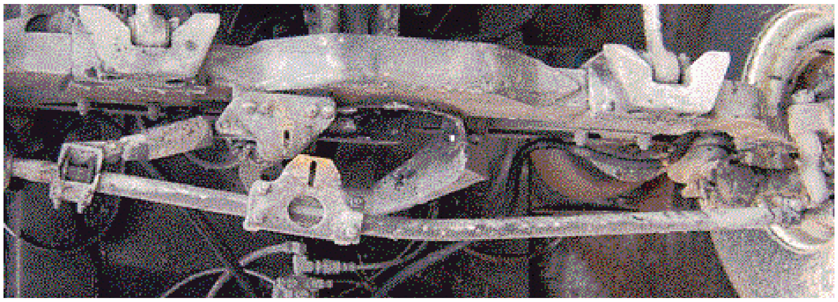


Figure 54- Americanos 60630 Signature Bent Tie Rod

Figure 55- Greyhound 6352 Signature Bent Tie Rod

The Greyhound 6352 tie rod was installed on the VRTC test bus to illustrate and confirm that the impact markings on the tie rod could be caused by contact from a freed, rotating driveshaft. Figure 56 illustrates the rotational impact to the tie rod and the forced directional movement of the tie rod to the left as it strikes the latching plate assembly.

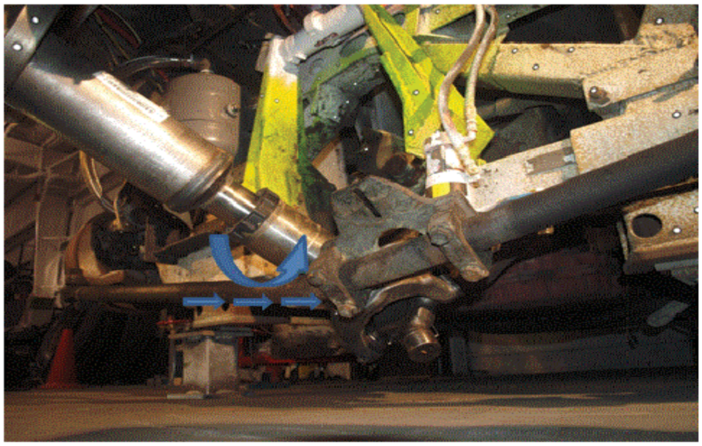


Figure 56- Driveshaft Impacting on Tie Rod Illustration

The impact marks on the Greyhound 6352 tie rod are shown in Figure 57, with the line of force and deflection axis illustrated in reference to the blows delivered by the freed driveshaft. Note once again the rotational markings embedded in the impact indentations.

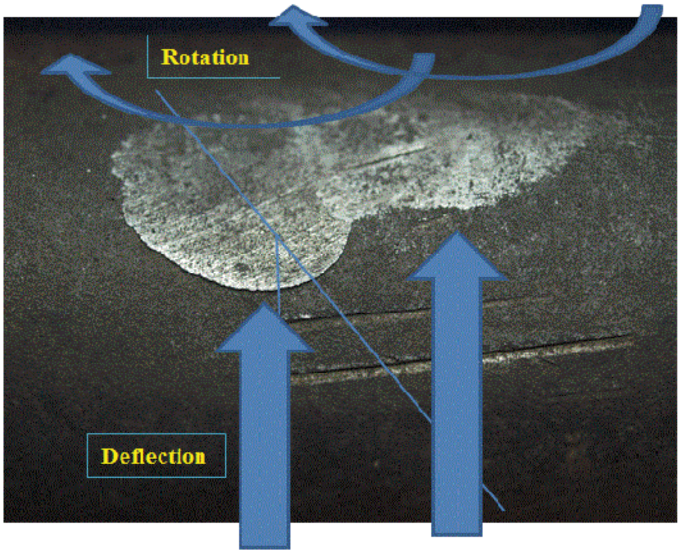


Figure 57- Greyhound 6352 Tie Rod Illustrated Impact Force Axis

Figure 58 shows the tie rod latching plates deformed and separated as the tie rod continued to bend down and away from the axle. It also shows the impact damage to the pneumatic latching cylinder and the mounting base as the counterclockwise rotation of the driveshaft forced it to impact the latching assembly. Once the latch is defeated, additional continuous impacts from the driveshaft force the steering knuckles of the tag axle to the left.

Figure 58- Greyhound 6352 Defeated Tag Axle Tie Rod Latch

5.3.4 Characterization of Caster Latches

In the Americanos 60630 crash, the caster latching tongue assembly and pneumatic cylinder clevis were both deformed and twisted as a result of the broken driveshaft end levering behind one of the caster arms. This physically forced the caster latch into a hyper extended negative caster position, tearing metal on the arm and defeating the latching tongue as the axle rolled forward into negative caster. A broken metal ramp piece from the latch tongue was found on the roadway near the beginning of the incident. Figure 59 shows the displaced and torn metal of the caster arm and the levering path the driveshaft took to force the arm forward into a negative caster position.

Figure 59- Americanos 60630 Caster Arm Levered Into Negative Caster by Driveshaft

Figure 60 is a top view mechanical illustration showing the caster latching tongue mounting through the rubber bushings. The perpendicular mounts use rubber bushings that allow upward deflection of the tongue when the cylinder extends into a ramp feature on the bottom of the tongue. This action forces the tongue upward to the unlocked caster position. When the cylinder retracts, the elastic feature of the bushings, as well as gravity, bring the tongue back down to a locked position. The elasticity of these bushings provides the uncontrolled mobility of the tongue when it is transitively impacted by the axle structure.

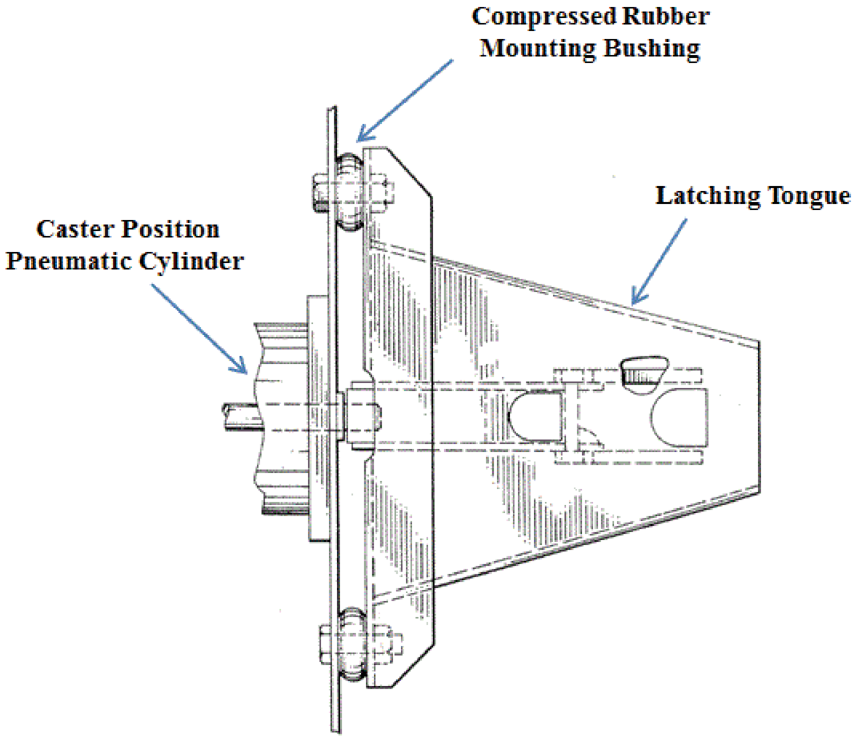


Figure 60- Mechanical Illustration of Caster Latching Tongue and Bushings

This photo of Greyhound 6352 in Figure 61 also shows the impact path into the caster arm assembly that occurred during the crash. The tag axle will continue to perform as a fixed axle if the tie rod is still intact; however both the tie rod and the caster control were damaged in the studied crashes. When a freely steering axle is combined with negative caster, it can destabilize tracking.

Figure 61- Greyhound 6352 Arrangement of Components that Affect Latching Tongue

Impact damage to the main caster latch arm assembly tube can be seen in Figure 62. A test was performed at VRTC, where the underside of the latch arm assembly was struck with an upward motion using a handheld steel bar. The impact caused the cantilevered latching tongue to bounce. This test demonstrated the latch could be overcome by a heavy impact that could translate through the latch arm structure, and could cause the latching tongue to bounce as a result of being mounted in a cantilever fashion, while also being fastened with rubber bushing mounts. Forces associated with this degree of impacting could translate through the arm and release the latching tongue.

Figure 62- Americanos 60630 Heavy Impact Damage to Caster Latch Arm

A series of dynamic vehicle tests were conducted that showed that common perturbations such as potholes and railroad crossings were adequate to bounce the latching tongue into an unlatched condition, rolling the axle forward into a negative caster if adequate brake force was also applied. With the tongue unlatched, the pullback force of the pneumatic caster position cylinder is insufficient to overcome the brake torque produced by the tag axle brakes. Figure 63 shows three test runs overlaid where a brake application was performed while driving over a simulated railroad crossing at VRTC's test facility. The graph clearly shows the tag axle caster position changed due to the tongue unlatching, while brake torque successfully rotated the axle forward into a negative caster position.

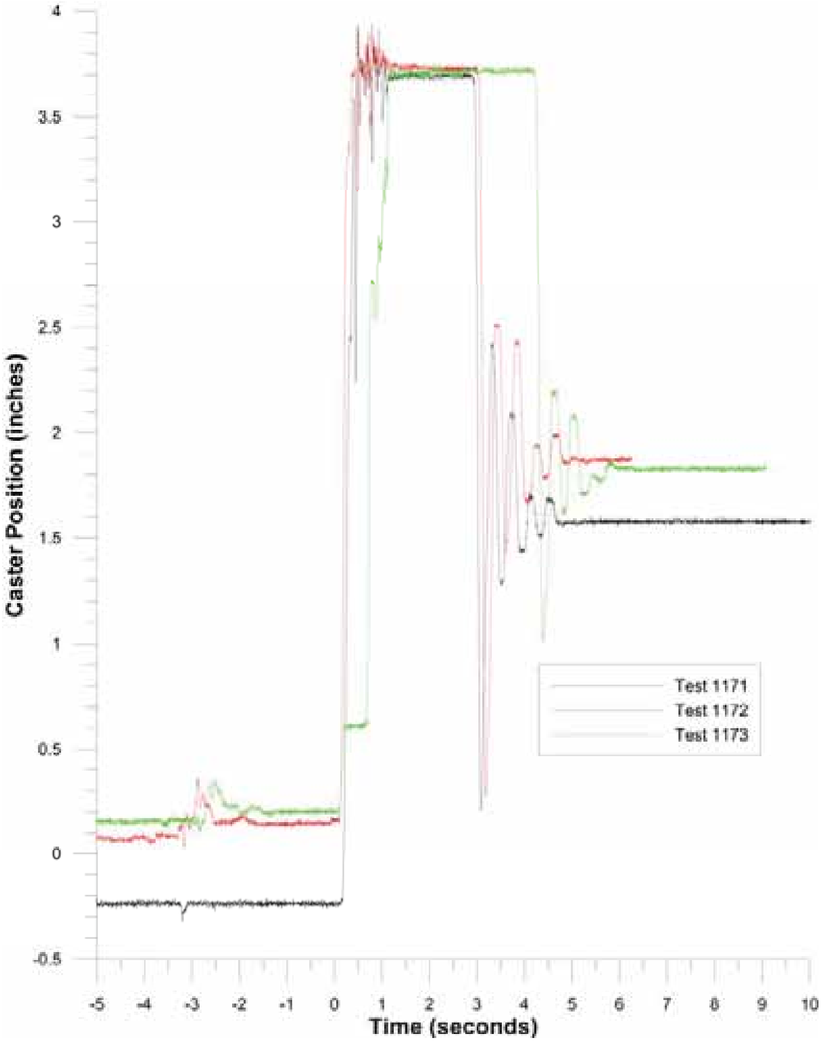


Figure 63- Impact Transmitted Caster Latch Failure Test Graph

5.4 Conclusions from Reconstruction

Analysis of the submitted evidence from Greyhound 6352 provides information regarding the sequence of events that led to the vehicle's loss of control. The evidence identified the failure mode and destructive capabilities of the failed driveshaft, as well as its effects. The evidence facilitated understanding of the physics involved in these failures.

5.4.1 Root Failure Cause

It was concluded that the precipitating event that caused the studied driveshafts to fail was a fracture of at least one of the thin-walled journal bearing ears of each driveshaft. The driveshafts from the reported occurrences investigated all experienced at least one of the cast ears fracturing through the centerline of the bearing cap retaining plate bolt holes. Figure 64 shows a cross section of the Greyhound 6352 driveshaft with the reassembly of the U-joint in the cast bearing journal at the fracture surface. There were no indications of deferred maintenance of the U-joint in any of the studied cases. Detection of the defect prior to failure would be unlikely because the failure exhibited no discernible warning through visual observation, service maintenance, or abnormal operation of the driveline.

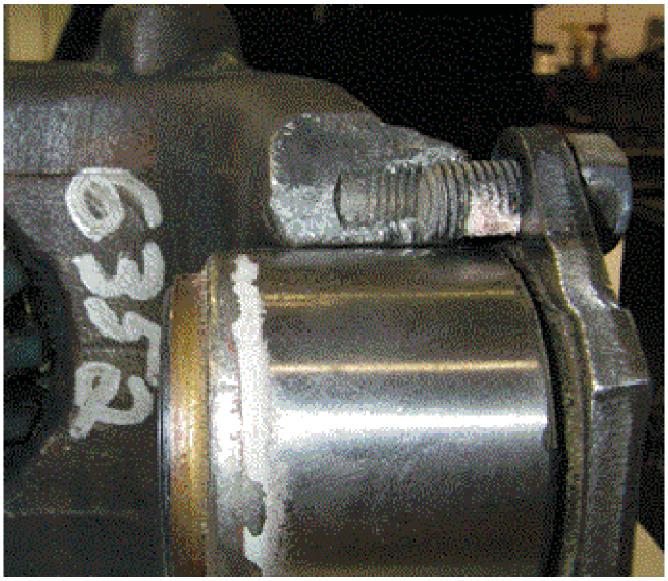


Figure 64- Greyhound 6352 Reassembled Fractured Bearing Journal

5.4.2 Driveshaft Escaping by Over-Compression

The examination of all subject evidence driveshafts indicated an over-compressed condition of the splined tubes. This over-compression made driveshaft escape easier because it effectively shortened its overall length. As the flailing shaft impacted the surfaces around the opening, it displaced metal by gouging and levering against the structure. This damage is seen in Figure 65 at the upper and leading edges of the opening. As the driveshaft escaped, it also levered against the face of the main axle beam, as shown in the Figure 65. Column fracturing occurred to the outer tube as the conical shape of the inner tube's mating end acted as a conical wedge that split the outer tube and allowed excessive shortening of the driveshaft. The compressive lengths of the failed driveshafts examined were inadequate to be retained properly by the designed D-Series tag axle structure of the subject class vehicles.

Figure 65- Greyhound 6352 Illustrating Driveshaft Levering Against Axle Face

5.4.3 Tie Rod Impacting Effects

Submitted evidence indicated that when a driveshaft decouples from the transmission, the driveshaft can escape containment and create significant damage to the vehicle. The high-force impacts can compromise components that include the tag axle steering controls. Evidence showed the signature bending of the tie rods from both crashes were due to downward strikes from the driveshaft.

When the initial strikes to the tie rod occur, geometry changes to the tie rod that draw the wheels inward are limited to the right rear wheel because the locking plate mounted to the tie rod isolates the left rear wheel. A toe-in condition of the right wheel results from the shortened effective length of the bent tie rod, and this condition is indicated by a single skid mark, as seen in the Americanos 60630 crash. Subsequent driveshaft strikes deform the tie rod further, until the locking mechanism is also defeated, which then allows the steering knuckles to freely swing as shown in Figure 66. The counterclockwise rotation of the driveshaft is also capable of producing repeating lateral strikes to the latch clamp on the tie rod, which can produce a lateral force input to the steerable tag axle. While an almost neutral caster angle may not affect steering, a significant lateral force input from the driveshaft yoke can provide sufficient force to drive the wheels to an excessively steered position. Testing that will be discussed in Section 7.1 demonstrated that once a sufficient force was imparted, the drag force of the sliding tire did not allow the steered wheels of the tag axle to return to a centered position.

Figure 66- Greyhound 6352 Separated Tie Rod Latch Plates

5.4.4 Defeated Caster latching

Several conditions can be created when a driveshaft decouples from the transmission that can lead to a compromise of the functionality of the tag axle caster position latching mechanism. Impacts to the caster latch arm assembly, as shown in Figure 67, can produce resonating forces through the structure causing the latching tongue to bounce. The axle can roll into a negative caster under moderate braking if the latch is defeated. The pneumatic position cylinder has inadequate force to keep the axle in the retracted home position under moderate braking if unlatching occurs. In the case of the Americanos 60630 crash, evidence showed the caster latch arm assembly was levered forward as the driveshaft wedged in behind the arms. The wedge forced the caster arms to roll forward into an extreme negative caster position, compounding the existing loss of stability of the steering knuckles. Damage and deformation of the tongue latching components and torn metal on the left caster arm are evidence of the levering caused by the driveshaft on the latch arm assembly.

Also, the caster latch tongue can be defeated without a driveshaft failure by resonating impact forces from common roadway perturbations under moderate braking conditions. This caster change can occur if the roadway impact is coincident with a firm brake application. If the tie rod is still latched in a non-steered condition in this scenario, there is little effect on the vehicle dynamics. If the tie rod is also released, which could occur from damage resulting from a broken driveshaft, the steering knuckles are able to react to the caster angle changes. In both the

Americanos 60630 and the Greyhound 6352 crashes, a caster change occurred during the course of the event resulting from impacting damage from the driveshaft. This unintentional caster change contributed as a dynamic function to the loss of control of the tag axle steering knuckles in both crashes.

Figure 67- Greyhound 6352 Illustrating Impacting Caster Latch Arm Assembly

6.0 STATIONARY VEHICLE TESTING USING APPLIED FIXTURES

The VRTC test vehicle was used as a stationary test platform to conduct several specialized measurements by applying unique fixtures to the tag axle and related components. These tests were performed to confirm theories and assist in quantifying manufacturer's dimensions and the performance levels of specific components functionality.

6.1 Tag Axle Caster Angle Change Fixture

Verification of the 6° tag axle caster change and axle roll was measured using machinist alignment lasers. Lasers were mounted to the center hub axis and through the center line of steering knuckle king pin. The laser positions were projected on a level floor recording both the home and reverse caster locations of the axle and the tire roll as the axle changed positions. The caster measurement using the lasers is shown in Figure 68.

Figure 68- Measuring Caster Angle Change on VRTC Bus Using Lasers

6.2 Axle Caster Pneumatic Cylinder Pull-Back Force Fixture

A hydraulic ram and load cell were applied to the tag axle caster arm structure, as shown in Figure 69, to measure the pull-back force the caster position cylinder produced. The caster latch was unlatched and the axle was pulled into the reverse caster position until it reached the safety catch. The test was used to determine the amount of brake torque that would be required to overcome the position cylinder if the latch was defeated and rotate the axle into a negative caster position.

Figure 69- Pulling Caster Arms to Safety Catch on VRTC Bus

6.3 Tag Axle Caster Latch Impact Fixture

A pneumatic impacting fixture was constructed and applied to the VRTC test bus to confirm that when a driveshaft strikes the caster arms, the force can be transmitted through the arms and into the latching plate and cause it to release the caster lock. A solid steel bar was projected by a pneumatic lever actuator into the cross tie tube of the caster arms directly under the latching tongue. This impact point matches the damage area found on the evidence axles. High speed video cameras recorded the event and captured the bouncing of the latching tongue as the forces transmitted easily through the structure when impacted. Figure 70 and 71 show the test fixture in place under the tag axle caster latch arm assembly. An accelerometer was attached to the accelerated 22-pound mass to calculate impacting forces.

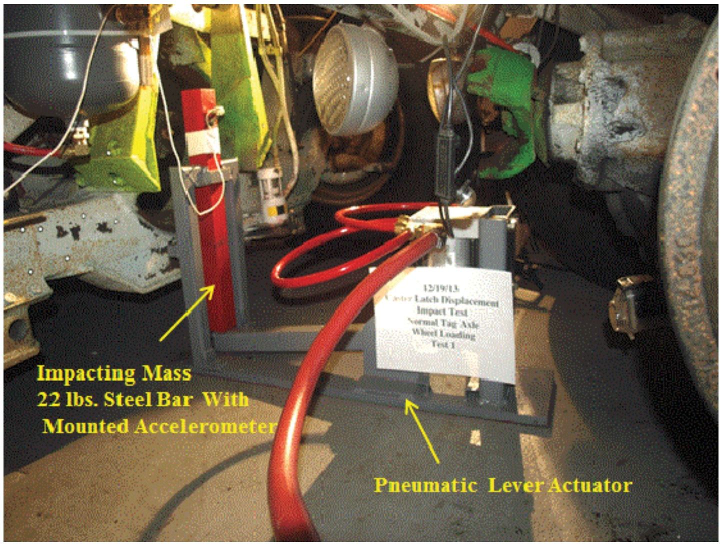


Figure 70- Caster Latch Arm Assembly Impacting Test Fixture

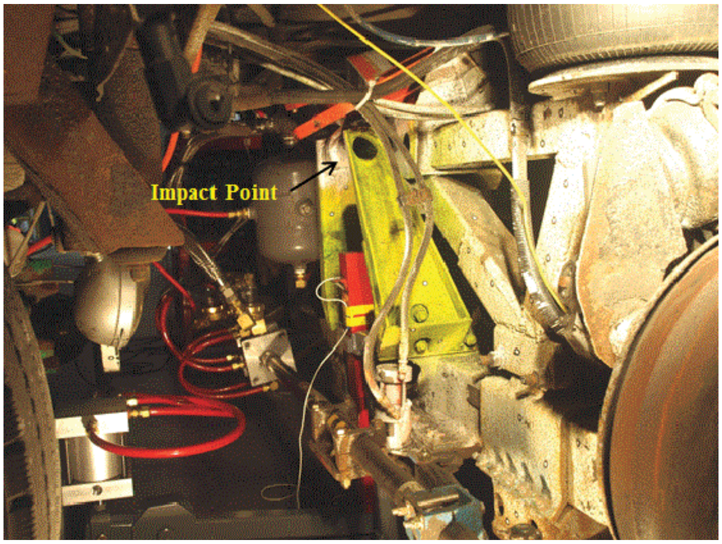


Figure 71- Impact Test of Upper Caster Latch Assembly on VRTC Bus

6.4 Tag Axle Radius Rods Compliance Fixture

To measure the compliance of the tag axle radius rods and the drive axle mounting links, a hydraulic ram and load cell was positioned between the two axles as shown in Figure 72. Force was applied to yield all bushing compliance of the rods and mounting links on both axles. The displacement is shown being measured in Figure 73. This displacement can occur when the driveshaft levers off the face of the tag axle as it escapes. There was minimal difference found between the bushing compliance of both new and used radius rods tested on the tag axle.

Figure 72- Loading Axles on VRTC Bus with Hydraulic Ram

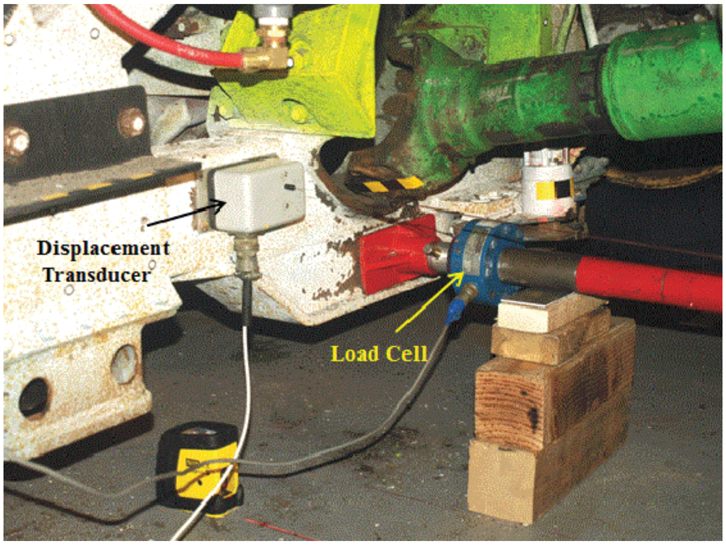


Figure 73- Measuring Compliance of Axle Radius Rods

6.5 Tag Axle Tie Rod Bending Fixture

A test was conducted to replicate the signature V-shaped tension bend found on tie rods from both the Americanos 60630 and the Greyhound 6352 crashes. A hydraulic cylinder was positioned to apply force in the same axis as the freed driveshaft. The driveshaft contacted the tie rod at the same location as the strike points located on the evidence tie rods. The ram assembly and load cell is shown bending the tie rod with the freed driveshaft in Figure 74. A slow continuous rate of force was applied using a hand pump while instrumentation data and video was collected.

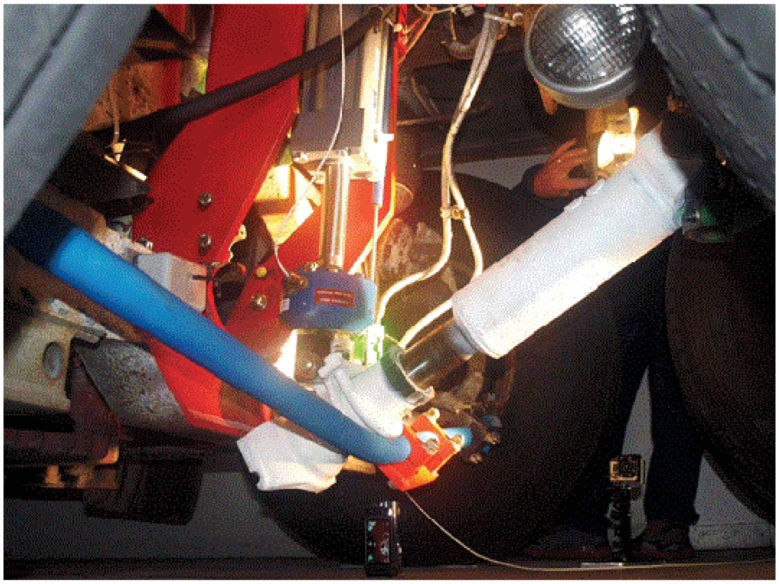


Figure 74- Signature Bending of Tie Rod with Hydraulic Ram on VRTC Bus

The forces required to displace the tie rod were significantly below predicted striking forces from an approximately 90 pound driveshaft rotating at 2,000 RPM. Even without direct impact damage to the latching cylinder and mounting block, the cantilevered latching plates were easily defeated by leverage as the tie rod bent to the signature shape. Figure 75 shows the deformed lower latch late that was levered downward by the tie rod plate as the bending progressed. The test also confirmed that only the right tag axle tire toes inward during the initial bending of the tie rod. The wheel remains toed in with the left wheel still straight ahead until the tie rod latch is defeated. This was the same tire orientation that produced the single tire mark in testing (see section 7.3) and most likely at the beginning of the Americanos 60630 crash.

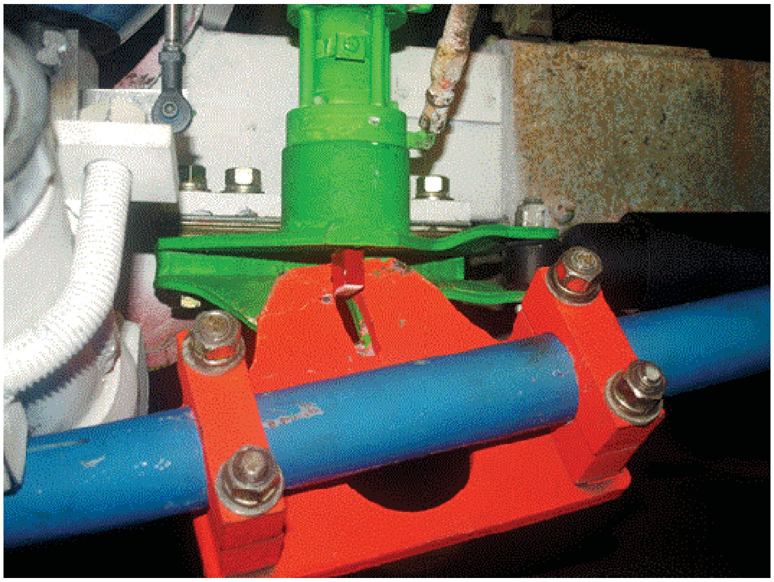


Figure 75- Defeated Latch Plates Yielded from Signature Bending

7.0 DYNAMIC VEHICLE TESTING

7.1 Testing for Understanding

Vehicle dynamic testing started with low speed trials and learning maneuvers to develop an understanding of tag axle performance. Since the conditions of the accidents were unique due to a steerable tag axle possibly influencing loss of control, there was no prior testing or research available for reference. Figure 76 shows a forced steer condition test using the pneumatic tie rod push cylinders that were shown in Section 4 of the report. This type of test was used to determine whether the steerable tag axle had the capability to steer the back of the bus under different caster positions and pavement conditions.

Figure 76- VRTC Bus Forced Tag Axle Steering Trial Testing

Other trial tests included low speed releasing of the tie rod with different caster positions applied to the tag axle. These tests established the stability of the steering knuckles of the tag axle when the tie rod is unlatched. Additional tests were conducted using low coefficient surfaces so reduced speeds could be used for safe testing. Figure 77 shows the test unit being steered into a 90° yaw by the tag axle on a low-friction wet surface. The drive wheels ahead of the tag axle wheels were able to lock easily and thus reduced rear lateral stability. When the tag axle tie rod was released with a reversed caster position, the steering knuckles swung violently into their stop bolts, and the back of the bus yawed uncontrollably. Additional trial tests confirmed the importance of maintaining a positive caster for stability of the steering knuckles of the tag axle when the tie rod was unlatched.

Figure 77- VRTC Bus Tag Axle Steering with Reversed Caster Test

7.2 Induced Failed Conditions Tests

The results of the low speed trial learning tests demonstrated that certain theorized conditions can produce a degree of steering loss by the tag axle. The test vehicle was fitted with outriggers so a more aggressive level of testing could be conducted safely. Tests were performed with different combinations of failed conditions to access any loss of controllability and the effects of counter steering and braking during these events. Although the test vehicle was equipped with outriggers, the test maneuvers were still performed at speeds much slower than the actual reported accidents that occurred at highway speeds. Even at reduced speeds, the tests showed again that certain failure modes of tag axle components will contribute to steering loss of the vehicle. Figure 78 below shows the VRTC test vehicle performing an aggressive maneuver with corrective steering efforts applied by a professional test driver.

This more aggressive level of testing demonstrated that the effects of the tag axle failures could produce yawing that resulted in lane departure. The severity of compromise to steering control of the bus was also influenced by other causative factors. Vehicle speed and pavement conditions were elements that could increase the degree of loss of control and reduce recoverability by the driver. This series of tests also confirmed that when the positive caster position of the tag axle was being forced into a negative position while in forward motion, the stability of the steering knuckles was reduced when the tie rod was unlatched. Improper caster position is one of the key elements necessary for compromise of steering control if the tie rod is released during a failure event.

Figure 78- VRTC Test Vehicle Performing Aggressive Failure Test

7.3 Evidence Findings Validation Tests

Additional test fixtures such as the adjustable toe-change tie rod, previously shown in Section 4 of the report, were fitted to the vehicle to conduct induced failure mode testing. Americanos 60630 and the Greyhound 6352 crashes revealed specific failures of tag axle components. Tests were designed to replicate these failures and quantify the results. Shown in Figure 79 is the VRTC test vehicle reproducing the single tire marking found at the Americanos 60630 crash scene. This test showed the effects of the initial toe change that occurs to the tag axle tie rod from the first impacts from the driveshaft. The test also proved that aside from the induced toe-change, no braking or other additional elements are required to produce the tire marking. The toe-in condition applied to the VRTC right tag axle wheel was comparable to the amount of toe-in that would be produced by the signature bent tie rods examined from the crashes.

Other evidence findings were tested, such as the inadvertent release of the caster latch tongue using both evidence and exemplar parts. These tests demonstrated the ability for the latch tongue to fail under certain conditions, and that the failure is another element needed to achieve an unstable steering condition of the tag axle. This failure of the tongue latch allows the axle to have the ability to rotate into a negative caster during an unstable steering condition event. The effects of braking and counter-steering during failure events were also tested to confirm that locking of the tandem drive wheels without locking the tag axle wheels is possible and will provide increased steering authority to the tag axle.

Figure 79- VRTC Test Vehicle Replicating Accident Single Tire Marking

8.0 TESTING RESULTS SUMMARY

The combination of the static fixture testing and the dynamic vehicle tests performed by VRTC provided creditable information that confirmed the developed theories derived from the engineering analysis. The testing results were conclusive in defining quantifiable answers to specific questions regarding the accidents and non-crash incidents.

8.1 Conclusive Evidence Testing

The reassembly and tests performed on the evidence parts recovered from both the Americanos 60630 and the Greyhound 6352 crashes demonstrated conclusive confirmation of the alleged defect. The tests performed using the evidence parts assembled in a bench fixture showed that a decoupled driveshaft can escape from the tag axle pass-through allowing it to strike and damage critical steering and safety components of the tag axle. The effects on controllability based on the evidence findings were reinforced through the vehicle dynamic testing performed. This validation testing identified the combination of key element failure conditions necessary to produce a compromise to vehicle stability.

8.2 Conformation of Evidence Findings

VRTC's testing also successfully reproduced critical crash evidence findings such as the single tire marking of the Americanos 60630 scene and the signature tension bending of the tie rod that matched the Greyhound 6352 evidence. The results of these tests substantiated the theorized damage created to the tag axle and the resulting adverse effects that were produced by the decoupled driveshafts of the crash accidents. This testing also identified previously unknown performance problems of critical components, such as the caster position latch tongue function and the ability for brake torque to overcome the pullback force of the positon pneumatic cylinder allowing the caster of the axle to change.

8.3 Testing Documentation

The testing performed for both applied test fixtures and the controlled dynamic vehicle maneuvers provided NHTSA with measurable data recorded instrumentation files supported by high definition video imaging. These test data files with video imaging were used as the format for testing documentation. The applied electronics instrumentation being recorded during testing generated quantifiable data files that established the correlation between the evidence findings and actual testing. High definition video imaging recorded in all the testing conducted verified the test data and findings.

9.0 INVESTIGATION FINDINGS AND CONCLUSIONS

The crashes studied in this investigation were a result of a series of events that began with the mechanical failure of the driveshafts in Americanos 60630 and the Greyhound 6352 crashes. The driveshaft failures created a chain reaction of equipment failure that ultimately caused a malfunction of key controllability components of the steerable tag axle system. These conclusions are based on the forensics evidence and testing conducted by VRTC.

9.1 Findings and Conclusions

- <u>Root cause:</u>
  The root cause of the driveshaft failure occurs as a direct result of the cast yoke journal ears fracturing. All yokes collected from the crashed buses displayed a common fracture line through the center axis of the bearing retainer cap bolt holes of the cast ear. Reassembly of evidence parts and the locations of recovered pieces documented in the accident scene reports confirmed the fracturing of the yoke cast ear occurring at the initiation stage of the incident.
- <u>Detectability level:</u>
  There were no indications of improper maintenance or that maintenance was required that would have prevented the incidents. Additionally, the U-joints were found to be in good working condition at the time of the incidents. Finally, records of driver interviews indicated a sudden onset of the failure with no warning.
- <u>A failed driveshaft will not be adequately contained by the driveshaft loop:</u>
  The reassembled evidence from the Greyhound 6352 tag axle and driveshaft parts showed that the driveshaft can escape <u>the pass-through (containment) structure</u> following a yoke failure event. The dynamics of the flailing driveshaft allows the broken end of the shaft to progress around the edge of the pass-through (containment) structure and force an exit path. While exiting the pass-through, the driveshaft levers against the face of the tag axle and can cause an over-compressed condition. This conclusion is substantiated by witness marks observed on all studied events.
- <u>Forced steering condition created:</u>
  The driveshaft failure can create a forced steering condition when the tie rod is deformed by impacting blows of the flailing shaft. This conclusion is supported by parts examined from the Americanos 60630 and the Greyhound 6352 crashes. Both tie rods exhibited displacement of the clamping mechanism for the latching plates resulting from direct strikes to the end of the blocks from the freed driveshaft's rotation. The repeated impacts to the clamp mechanism forced the steering knuckles and tag axle wheels to be pushed into a forced steer condition.

9.2 Summary of the Chain of Events

- The driveshaft yoke fails resulting in the driveshaft decoupling from the transmission hub and eventually escaping the tag axle pass-through (containment) structure.
- The driveshaft impacts the tie rod causing sufficient bending to defeat the latching plates, allowing the tie rod and steering knuckles to swing.
- A forced steering of the tie rod occurs from continuous rotational impacts of the driveshaft to the latching plate clamp block on the tie rod.
- The caster position latching tongue fails from driveshaft impacts or levering and frees the axle, allowing forward rotational movement into negative caster.
- A caster change in the negative direction occurs due to axle roll from braking or being forcefully levered by the driveshaft once the latching tongue fails.

<u>With the negative angle caster change, the steerable tag axle wheels are prevented from returning to a straight orientation and cause the rear of the bus to swing out of a straight travel direction.</u>

9.2.1 Other Elements That Can Influence the Severity of the Failure Chain

- Vehicle speed and weight will directly affect the amount of kinetic energy of the bus. Higher speeds create a more energetic rotating driveshaft that can impart greater force to the tag axle components.
- Roadway conditions that are wet or have deteriorated surfaces can reduce fiction levels, lowering thresholds for wheel lockup and sliding. Lower friction surfaces also affect counter braking and steering capabilities.
- Any loss of lateral stability that is normally created by the drive axle tandems increases the authority the tag axle has to steer the backend of the bus. If any of the tandem dual tires are deflated or are in a lock and slide braking condition, lateral stability of the vehicle decreases giving greater steering authority to the tag axle. If the drive axle tandems all lock and slide at the same time, the tag axle may exert steering authority if the tie rod is free.

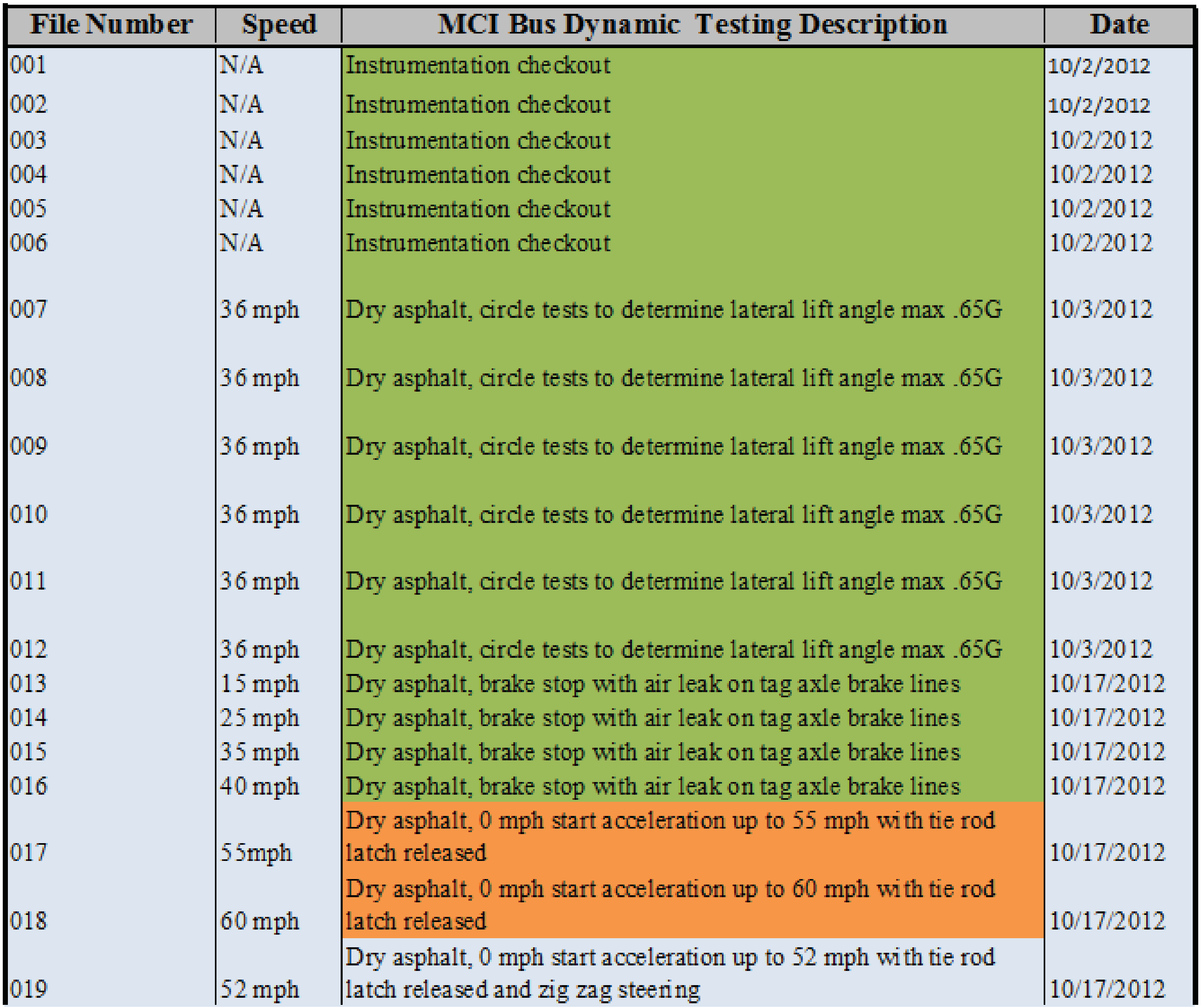
10.0 REFERENCES

N/A

11.0 APPENDIX

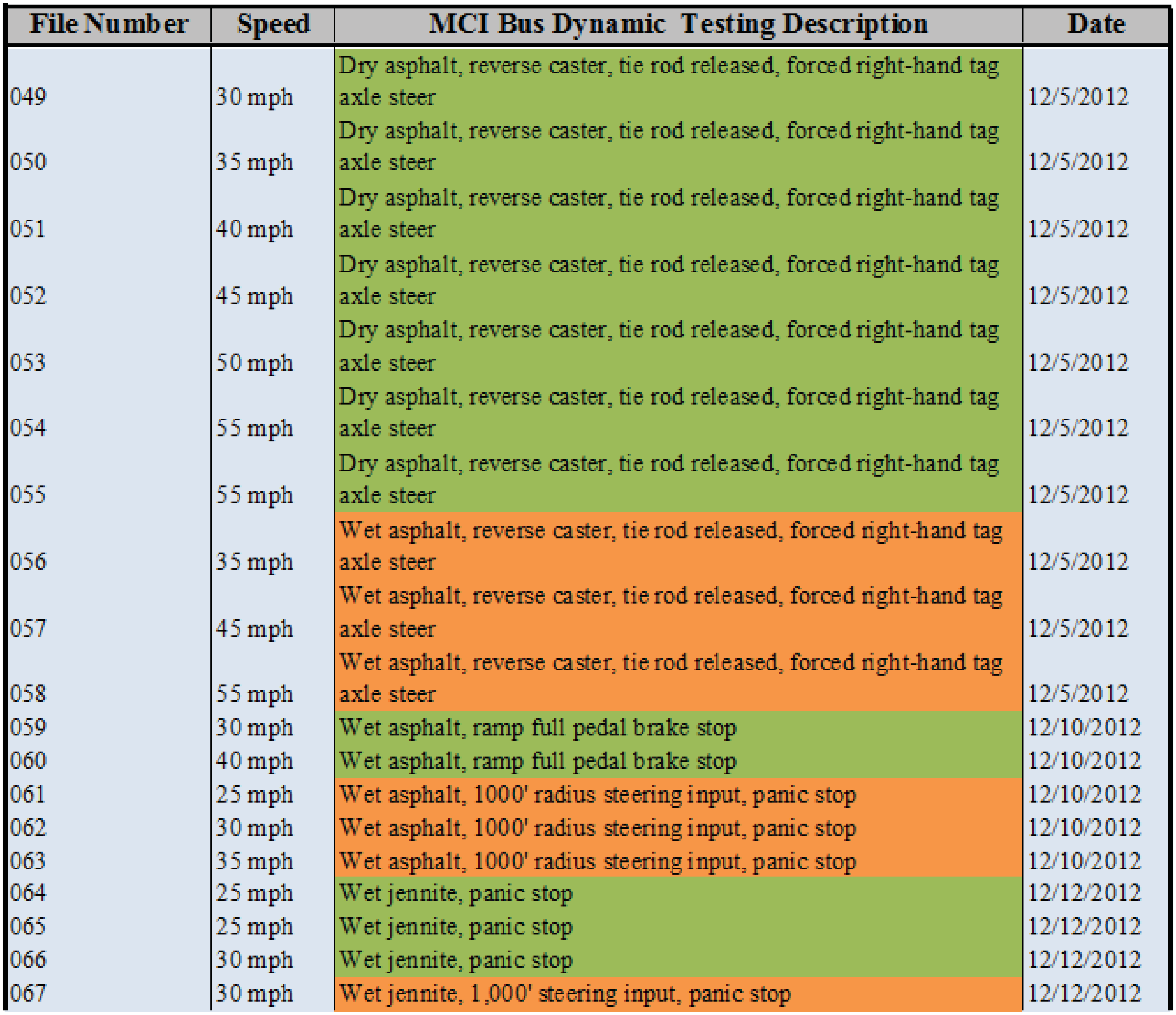
VRTC Test Vehicle Dynamic Test Run Register

The following appendage depicts all vehicle dynamic test runs performed by NHTSA at the test facilities. The documentation includes the date of each test, a file number that correlates to data files collected and a description of the maneuver performed.



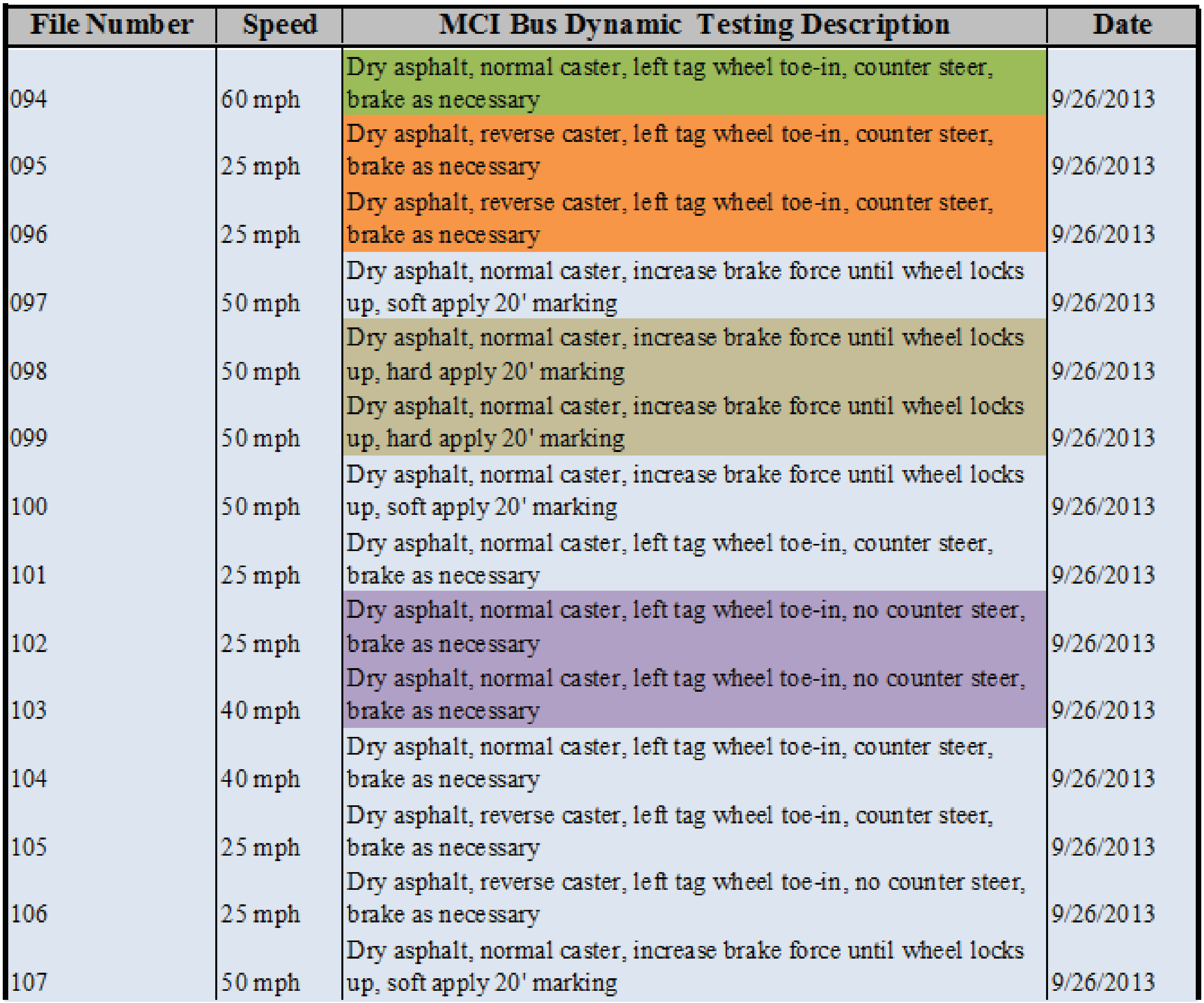
File Number	Speed	MCI Bus Dynamic Testing Description	Date
001	N/A	Instrumentation checkout	10/2/2012
002	N/A	Instrumentation checkout	10/2/2012
003	N/A	Instrumentation checkout	10/2/2012
004	N/A	Instrumentation checkout	10/2/2012
005	N/A	Instrumentation checkout	10/2/2012
006	N/A	Instrumentation checkout	10/2/2012
007	36 mph	Dry asphalt, circle tests to determine lateral lift angle max .65G	10/3/2012
008	36 mph	Dry asphalt, circle tests to determine lateral lift angle max .65G	10/3/2012
009	36 mph	Dry asphalt, circle tests to determine lateral lift angle max .65G	10/3/2012
010	36 mph	Dry asphalt, circle tests to determine lateral lift angle max .65G	10/3/2012
011	36 mph	Dry asphalt, circle tests to determine lateral lift angle max .65G	10/3/2012
012	36 mph	Dry asphalt, circle tests to determine lateral lift angle max .65G	10/3/2012
013	15 mph	Dry asphalt, brake stop with air leak on tag axle brake lines	10/17/2012
014	25 mph	Dry asphalt, brake stop with air leak on tag axle brake lines	10/17/2012
015	35 mph	Dry asphalt, brake stop with air leak on tag axle brake lines	10/17/2012
016	40 mph	Dry asphalt, brake stop with air leak on tag axle brake lines	10/17/2012
017	55mph	Dry asphalt, 0 mph start acceleration up to 55 mph with tie rod latch released	10/17/2012
018	60 mph	Dry asphalt, 0 mph start acceleration up to 60 mph with tie rod latch released	10/17/2012
019	52 mph	Dry asphalt, 0 mph start acceleration up to 52 mph with tie rod latch released and zig zag steering	10/17/2012

File Number	Speed	MCI Bus Dynamic Testing Description	Date
020	55 mph	Dry asphalt, 0 mph start acceleration up to 55 mph with tie rod latch released and caster reversed	10/17/2012
021	50 mph	Dry asphalt, 0 mph start acceleration up to 50 mph with tie rod latch released and caster reversed and zig zag steering	10/17/2012
022	45 mph	Dry asphalt, ramp apply brake stop	10/17/2012
023	45 mph	Dry asphalt, ramp apply brake stop	10/17/2012
026	50 mph	Dry asphalt, best effort brake stop no air leak	11/15/2012
027	50 mph	Dry asphalt, best effort brake stop no air leak	11/15/2012
028	50 mph	Dry asphalt, best effort brake stop no air leak	11/15/2012
029	50 mph	Dry asphalt, ramp apply brake stop no air leak	11/15/2012
030	50 mph	Dry asphalt, ramp apply brake stop no air leak	11/15/2012
031	50 mph	Dry asphalt, ramp apply brake stop no air leak	11/15/2012
032	50 mph	Dry asphalt, best effort brake stop with air leak	11/15/2012
033	50 mph	Dry asphalt, best effort brake stop with air leak	11/15/2012
034	50 mph	Dry asphalt, best effort brake stop with air leak	11/15/2012
036	25 mph	Dry asphalt, normal caster, forced right-hand tag axle steer	11/28/2012
037	30 mph	Dry asphalt, normal caster, forced right-hand tag axle steer	11/28/2012
038	35 mph	Dry asphalt, normal caster, forced right-hand tag axle steer	11/28/2012
039	40 mph	Dry asphalt, normal caster, forced right-hand tag axle steer	11/28/2012
040	45 mph	Dry asphalt, normal caster, forced right-hand tag axle steer	11/28/2012
041	50 mph	Dry asphalt, normal caster, forced right-hand tag axle steer	11/28/2012
042	55 mph	Dry asphalt, normal caster, forced right-hand tag axle steer	11/28/2012
043	60 mph	Dry asphalt, normal caster, forced right-hand tag axle steer	11/28/2012
044	25 mph	Dry asphalt, reverse caster, forced right-hand tag axle steer	11/29/2012
045	35 mph	Dry asphalt, reverse caster, forced right-hand tag axle steer	11/29/2012
046	40 mph	Dry asphalt, reverse caster, forced right-hand tag axle steer	11/29/2012
047	40 mph	Dry asphalt, reverse caster, forced right-hand tag axle steer	11/29/2012
048	35 mph	Dry asphalt, reverse caster, forced right-hand tag axle steer	11/29/2012



File Number	Speed	MCI Bus Dynamic Testing Description	Date
049	30 mph	Dry asphalt, reverse caster, tie rod released, forced right-hand tag axle steer	12/5/2012
050	35 mph	Dry asphalt, reverse caster, tie rod released, forced right-hand tag axle steer	12/5/2012
051	40 mph	Dry asphalt, reverse caster, tie rod released, forced right-hand tag axle steer	12/5/2012
052	45 mph	Dry asphalt, reverse caster, tie rod released, forced right-hand tag axle steer	12/5/2012
053	50 mph	Dry asphalt, reverse caster, tie rod released, forced right-hand tag axle steer	12/5/2012
054	55 mph	Dry asphalt, reverse caster, tie rod released, forced right-hand tag axle steer	12/5/2012
055	55 mph	Dry asphalt, reverse caster, tie rod released, forced right-hand tag axle steer	12/5/2012
056	35 mph	Wet asphalt, reverse caster, tie rod released, forced right-hand tag axle steer	12/5/2012
057	45 mph	Wet asphalt, reverse caster, tie rod released, forced right-hand tag axle steer	12/5/2012
058	55 mph	Wet asphalt, reverse caster, tie rod released, forced right-hand tag axle steer	12/5/2012
059	30 mph	Wet asphalt, ramp full pedal brake stop	12/10/2012
060	40 mph	Wet asphalt, ramp full pedal brake stop	12/10/2012
061	25 mph	Wet asphalt, 1000' radius steering input, panic stop	12/10/2012
062	30 mph	Wet asphalt, 1000' radius steering input, panic stop	12/10/2012
063	35 mph	Wet asphalt, 1000' radius steering input, panic stop	12/10/2012
064	25 mph	Wet jennite, panic stop	12/12/2012
065	25 mph	Wet jennite, panic stop	12/12/2012
066	30 mph	Wet jennite, panic stop	12/12/2012
067	30 mph	Wet jennite, 1,000' steering input, panic stop	12/12/2012

File Number	Speed	MCI Bus Dynamic Testing Description	Date
068	35 mph	Wet jennite, 1,000' steering input, panic stop	12/12/2012
069	45 mph	Wet asphalt, 1,000' steering input, panic stop	12/18/2012
070	45 mph	Wet asphalt, 1,000' steering input, panic stop	12/18/2012
071	50 mph	Wet asphalt, 1,000' steering input, panic stop	12/18/2012
072	35 mph	Wet asphalt, 500' steering input, ramp stop	12/18/2012
073	35 mph	Wet asphalt, 500' steering input, ramp stop	12/18/2012
076	45 mph	Dry asphalt, straight line lite braking, normal caster	2/11/2013
077	50 mph	Dry asphalt, straight line lite braking, normal caster	2/11/2013
078	45 mph	Dry asphalt, straight line lite braking, reverse caster	2/11/2013
079	35 mph	Dry asphalt, 1000' radius steering input, lite braking, normal caster	2/11/2013
080	35 mph	Dry asphalt, 1000' radius steering input, lite braking, reverse caster	2/11/2013
082	35 mph	Dry asphalt, straight line normal braking, normal caster, forced right-hand tag axle steer and released	2/14/2013
083	55 mph	Dry asphalt, straight line normal braking, normal caster, forced right-hand tag axle steer and released	2/14/2013
084	35 mph	Dry asphalt, straight line normal braking, reverse caster, forced right-hand tag axle steer and released	2/14/2013
085	45 mph	Dry asphalt, straight line normal braking, reverse caster, forced right-hand tag axle steer and released	2/14/2013
086	55 mph	Dry asphalt, straight line normal braking, reverse caster, forced right-hand tag axle steer and released	2/14/2013
091	25 mph	Dry asphalt, normal caster, left tag wheel toe-in, counter steer, brake as necessary	9/26/2013
092	25 mph	Dry asphalt, normal caster, left tag wheel toe-in, no counter steer, brake as necessary	9/26/2013
093	40 mph	Dry asphalt, normal caster, left tag wheel toe-in, counter steer, brake as necessary	9/26/2013

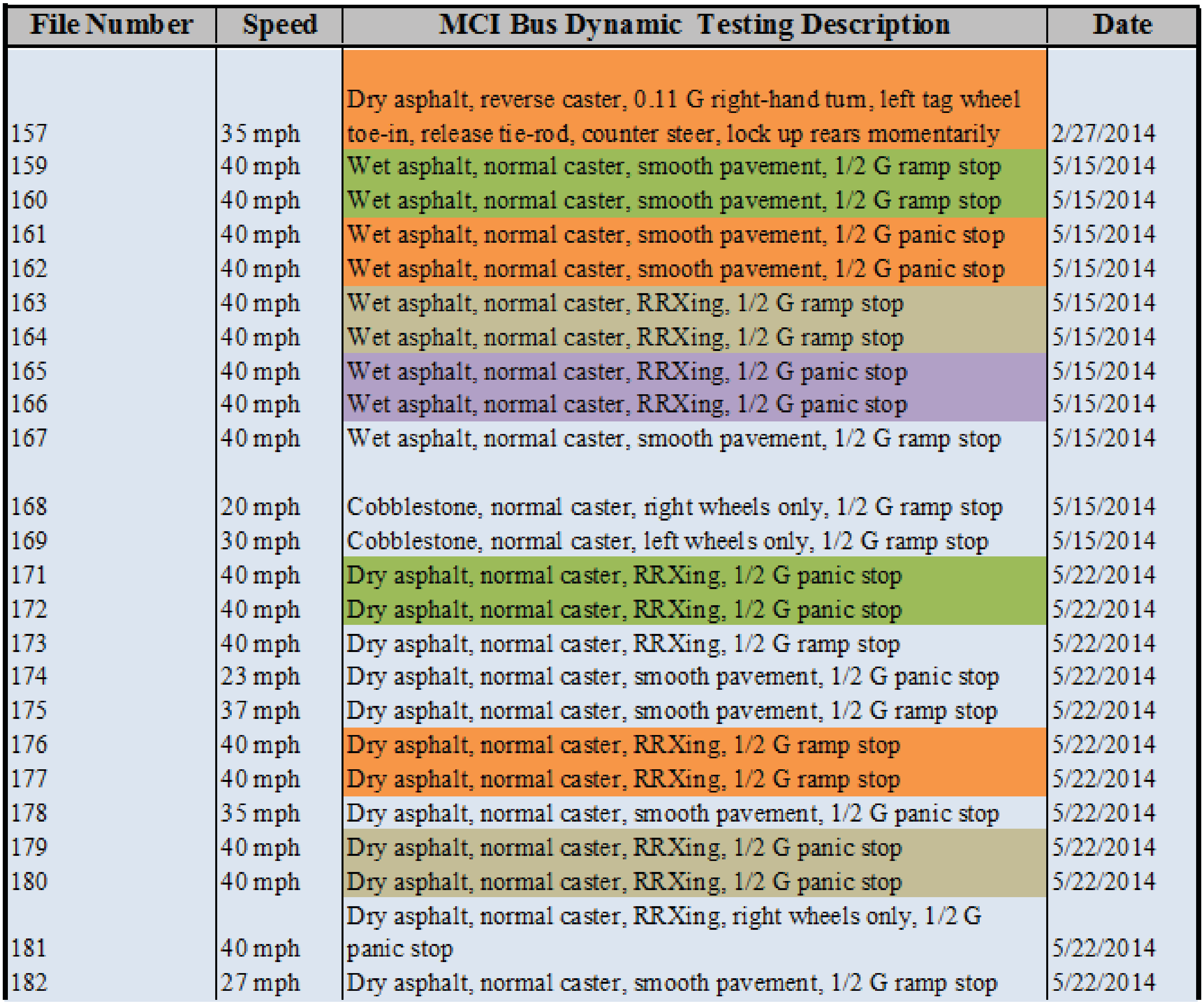


File Number	Speed	MCI Bus Dynamic Testing Description	Date
094	60 mph	Dry asphalt, normal caster, left tag wheel toe-in, counter steer, brake as necessary	9/26/2013
095	25 mph	Dry asphalt, reverse caster, left tag wheel toe-in, counter steer, brake as necessary	9/26/2013
096	25 mph	Dry asphalt, reverse caster, left tag wheel toe-in, counter steer, brake as necessary	9/26/2013
097	50 mph	Dry asphalt, normal caster, increase brake force until wheel locks up, soft apply 20' marking	9/26/2013
098	50 mph	Dry asphalt, normal caster, increase brake force until wheel locks up, hard apply 20' marking	9/26/2013
099	50 mph	Dry asphalt, normal caster, increase brake force until wheel locks up, hard apply 20' marking	9/26/2013
100	50 mph	Dry asphalt, normal caster, increase brake force until wheel locks up, soft apply 20' marking	9/26/2013
101	25 mph	Dry asphalt, normal caster, left tag wheel toe-in, counter steer, brake as necessary	9/26/2013
102	25 mph	Dry asphalt, normal caster, left tag wheel toe-in, no counter steer, brake as necessary	9/26/2013
103	40 mph	Dry asphalt, normal caster, left tag wheel toe-in, no counter steer, brake as necessary	9/26/2013
104	40 mph	Dry asphalt, normal caster, left tag wheel toe-in, counter steer, brake as necessary	9/26/2013
105	25 mph	Dry asphalt, reverse caster, left tag wheel toe-in, counter steer, brake as necessary	9/26/2013
106	25 mph	Dry asphalt, reverse caster, left tag wheel toe-in, no counter steer, brake as necessary	9/26/2013
107	50 mph	Dry asphalt, normal caster, increase brake force until wheel locks up, soft apply 20' marking	9/26/2013

File Number	Speed	MCI Bus Dynamic Testing Description	Date
108	50 mph	Dry asphalt, normal caster, increase brake force until wheel locks up, hard apply 20' marking	9/26/2013
109	25 mph	Wet jennite, normal caster, left tag wheel toe-in, no counter steer, no brake	11/7/2013
110	25 mph	Wet jennite, normal caster, left tag wheel toe-in, counter steer, no brake	11/7/2013
11	25 mph	Wet jennite, normal caster, left tag wheel toe-in, no counter steer, brake	11/7/2013
112	25 mph	Wet jennite, normal caster, left tag wheel toe-in, counter steer, brake	11/7/2013
113	25 mph	Wet jennite, normal caster, left tag wheel toe-in, no counter steer, lite braking	11/7/2013
114	25 mph	Wet jennite, normal caster, left tag wheel toe-in, no counter steer, lite braking	11/7/2013
115	25 mph	Wet jennite, normal caster, left tag wheel toe-in, no counter steer, lite braking	11/7/2013
116	25 mph	Wet jennite, normal caster, left tag wheel toe-in, no counter steer, lite braking	11/7/2013
117	25 mph	Wet jennite, reverse caster, left tag wheel toe-in, no counter steer, no brake	11/7/2013
118	25 mph	Wet jennite, reverse caster, left tag wheel toe-in, counter steer, no brake	11/7/2013
119	25 mph	Wet jennite, reverse caster, left tag wheel toe-in, no counter steer, brake	11/7/2013
120	25 mph	Wet jennite, reverse caster, left tag wheel toe-in, counter steer, brake	11/7/2013
121	25 mph	Wet jennite/wet asphalt split mu, normal caster, left tag wheel toe-in, steer off jennite, no counter steer	11/7/2013

File Number	Speed	MCI Bus Dynamic Testing Description	Date
122	30 mph	Wet jennite/wet asphalt split mu, normal caster, left tag wheel toe-in, steer off jennite, no counter steer	11/7/2013
123	30 mph	Wet jennite/wet asphalt split mu, reverse caster, left tag wheel toe-in, steer off jennite, no counter steer	11/7/2013
124	30 mph	Wet jennite, normal caster, tie rod released, no brake	11/7/2013
125	30 mph	Wet jennite, normal caster, tie rod released, brake	11/7/2013
127	30 mph	Wet jennite, normal caster, tie rod released, no brake	11/7/2013
128	30 mph	Wet jennite, normal caster, tie rod released, brake	11/7/2013
129	30 mph	Wet jennite, normal caster, tie rod released, brake, counter steer	11/7/2013
130	30 mph	Wet jennite, reverse caster, tie rod released, no brake	11/7/2013
131	30 mph	Wet jennite, reverse caster, tie rod released, brake	11/7/2013
133	30 mph	Wet jennite, reverse caster, tie rod released, no brake	11/7/2013
134	30 mph	Wet jennite, reverse caster, tie rod released, brake	11/7/2013
135	30 mph	Wet jennite, reverse caster, tie rod released, brake, counter steer	11/7/2013
136	30 mph	Wet jennite, reverse caster, tie rod released, brake, counter steer	11/7/2013
137	30 mph	Wet jennite, reverse caster, tie rod released, no brake	11/7/2013
138	30 mph	Wet jennite, reverse caster, tie rod released, brake	11/7/2013
139	30 mph	Wet jennite, reverse caster, tie rod released, brake, counter steer	11/7/2013
140	30 mph	Wet jennite, reverse caster, 0.11 right hand turn, tie rod released, brake, counter steer	11/7/2013
141	30 mph	Wet jennite, reverse caster, 0.11 right hand turn, tie rod released, brake, no counter steer	11/7/2013
142	30 mph	Wet jennite, reverse caster, 0.11 left hand turn, tie rod released, brake	11/7/2013

File Number	Speed	MCI Bus Dynamic Testing Description	Date
143	30 mph	Wet jennite, reverse caster, S-turn, right steer with brake, release when yaws, left turn fast input with brake	11/7/2013
144	30 mph	Wet jennite, reverse caster, S-turn, right steer with brake, release when yaws, left turn fast input with brake	11/7/2013
145	30 mph	Wet jennite, reverse caster, S-turn, right steer with brake, release when yaws, left turn fast input with brake	11/7/2013
148	48 mph	Dry asphalt, normal caster, 0.11 G right-hand turn, inside drive tire @50 psi, lockup rears momentarily	2/27/2014
149	48 mph	Dry asphalt, normal caster, 0.11 G right-hand turn, inside drive tire @50 psi, lockup rears momentarily	2/27/2014
150	48 mph	Dry asphalt, normal caster, 0.11 G right-hand turn, outside drive tire @50 psi, lockup rears momentarily	2/27/2014
151	35 mph	Dry asphalt, normal caster, 0.11 G right-hand turn, left tag wheel toe-in, no counter steer, no brake	2/27/2014
152	35 mph	Dry asphalt, normal caster, 0.11 G right-hand turn, left tag wheel toe-in, no counter steer, lock up rears momentarily	2/27/2014
153	35 mph	Dry asphalt, normal caster, 0.11 G right-hand turn, left tag wheel toe-in, release tie-rod, counter steer, lock up rears momentarily	2/27/2014
154	35 mph	Dry asphalt, reverse caster, 0.11 G right-hand turn, left tag wheel toe-in, release tie-rod, counter steer, no brake	2/27/2014
155	35 mph	Dry asphalt, reverse caster, 0.11 G right-hand turn, left tag wheel toe-in, release tie-rod, counter steer, lock up rears momentarily	2/27/2014
156	35 mph	Dry asphalt, reverse caster, 0.11 G right-hand turn, left tag wheel toe-in, release tie-rod, counter steer, lock up rears momentarily	2/27/2014



File Number	Speed	MCI Bus Dynamic Testing Description	Date
157	35 mph	Dry asphalt, reverse caster, 0.11 G right-hand turn, left tag wheel toe-in, release tie-rod, counter steer, lock up rears momentarily	2/27/2014
159	40 mph	Wet asphalt, normal caster, smooth pavement, 1/2 G ramp stop	5/15/2014
160	40 mph	Wet asphalt, normal caster, smooth pavement, 1/2 G ramp stop	5/15/2014
161	40 mph	Wet asphalt, normal caster, smooth pavement, 1/2 G panic stop	5/15/2014
162	40 mph	Wet asphalt, normal caster, smooth pavement, 1/2 G panic stop	5/15/2014
163	40 mph	Wet asphalt, normal caster, RRXing, 1/2 G ramp stop	5/15/2014
164	40 mph	Wet asphalt, normal caster, RRXing, 1/2 G ramp stop	5/15/2014
165	40 mph	Wet asphalt, normal caster, RRXing, 1/2 G panic stop	5/15/2014
166	40 mph	Wet asphalt, normal caster, RRXing, 1/2 G panic stop	5/15/2014
167	40 mph	Wet asphalt, normal caster, smooth pavement, 1/2 G ramp stop	5/15/2014
168	20 mph	Cobblestone, normal caster, right wheels only, 1/2 G ramp stop	5/15/2014
169	30 mph	Cobblestone, normal caster, left wheels only, 1/2 G ramp stop	5/15/2014
171	40 mph	Dry asphalt, normal caster, RRXing, 1/2 G panic stop	5/22/2014
172	40 mph	Dry asphalt, normal caster, RRXing, 1/2 G panic stop	5/22/2014
173	40 mph	Dry asphalt, normal caster, RRXing, 1/2 G ramp stop	5/22/2014
174	23 mph	Dry asphalt, normal caster, smooth pavement, 1/2 G panic stop	5/22/2014
175	37 mph	Dry asphalt, normal caster, smooth pavement, 1/2 G ramp stop	5/22/2014
176	40 mph	Dry asphalt, normal caster, RRXing, 1/2 G ramp stop	5/22/2014
177	40 mph	Dry asphalt, normal caster, RRXing, 1/2 G ramp stop	5/22/2014
178	35 mph	Dry asphalt, normal caster, smooth pavement, 1/2 G panic stop	5/22/2014
179	40 mph	Dry asphalt, normal caster, RRXing, 1/2 G panic stop	5/22/2014
180	40 mph	Dry asphalt, normal caster, RRXing, 1/2 G panic stop	5/22/2014
181	40 mph	Dry asphalt, normal caster, RRXing, right wheels only, 1/2 G panic stop	5/22/2014
182	27 mph	Dry asphalt, normal caster, smooth pavement, 1/2 G ramp stop	5/22/2014

File Number	Speed	MCI Bus Dynamic Testing Description	Date
183	40 mph	Dry asphalt, normal caster, shallow dip, right wheel only, 1/2 G panic stop	5/22/2014

U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

Memorandum

Vehicle Research & Test Center
PO Box B37
East Liberty, OH 43319

Subject: Final Report: 1992-2012 MCI D-Series Bus Driveshaft Failure

Date: NOV 25 2015

From: Tim Johnson
Director
Vehicle Research and Test Center

Reply to Attn. Of: NVS-310

To: Otto Matheke
Acting Director
Office of Defects Investigation

Attached is a copy of the final report titled, "1992-2012 MCI D-Series Bus Driveshaft Failure."

Attachment:
Final Report