STABILITY AND ON-ROAD PERFORMANCE OF MULTI-COMBINATION VEHICLES WITH AIR SUSPENSION SYSTEMS

STAGE 2 PROJECT

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Prepared by Roaduser Systems Pty Ltd
for the Remote Areas Group

STABILITY AND ON-ROAD PERFORMANCE OF MULTI-COMBINATION VEHICLES WITH AIR SUSPENSION SYSTEMS – STAGE 2 PROJECT – FINAL REPORT

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SUMMARY

In recent years there has been an increasing untilization of air suspension systems on heavy vehicle combinations due to the implementation of higher mass limits under the national mass limits review conducted during 1993-1996 [1]. by the then, National Road Transport Commission (NRTC). Whilst this is a desirable out come for productivity reasons, further work to provide guidance to operators and manufacturers in the best use and application of air suspension systems for various multi-combination vehicle configurations was considered necessary.

The primary areas of concern relate to multi-combination vehicles with air suspension systems that typically operate at high mass limits with high centre-of-gravity (COG) loads. There is strong anecdotal evidence that air suspension modifications on some vehicles are being undertaken to counteract some of the reported undesirable behaviours [1].

Reported undesirable behaviours included increased roll, sway and lurch of the vehicle making it difficult for the driver to control the combination. Drivers also reported that air sprung prime movers had a tendency to follow road indentations requiring a greater steering effort to keep the vehicle on its intended path. Air suspended dollies were reported to increase roll, reduce stability and behave erratically under heavy braking.

As a result, drivers reported a preference for spring dollies that they felt were safer and considered their use resulted in a combination that was much easier to control.

A survey conducted by Estill and Associates **Error! Reference source not found.** provided sufficient anecdotal evidence to make it apparent that guidelines for the use of air suspension systems in multi combination vehicles would be a positive safety initiative and of assistance to both manufacturers and operators alike.

Roaduser Systems Pty Ltd was subsequently commissioned to carry out computer simulations of these multi-combinations and Roaduser produced a report confirming the anecdotal evidence [3]. The then Department of Transport (WA) (Now Department for Planning and Infrastructure (DPI (WA)) managed and financed this report in conjunction with the then National Road Transport Commission (NRTC), now the National Transport Commission (NTC). Some financial assistance was also received from industry groups within the Remote Areas Group (RAG). The completion of this report concluded Stage 1 of the RAG Air Suspension Project.

There was some strong feeling amongst certain RAG members, supported by the manager of the project, that the theoretical computer simulations should be confirmed by physical instrumented testing of multi-combinations. To this end, the WA Livestock Association, Main Roads WA and DPI (WA) agreed to finance the second stage of the Project. The National Transport Commission (NTC) agreed to assist DPI (WA) in the administration of the contract.

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[1] The higher mass limits agreed in principle by Ministers in April 1998 required road-friendly suspensions certified to Vehicle Standards Bulletin (VSB) 11

Roaduser Systems was commissioned to carry out Stage 2 of the project. In the course of preparations for the vehicle testing, an opportunity arose to combine the Stage 2 testing with a separate, but related project for Main Roads WA, which involved testing of the acceleration and deceleration performance of combination vehicles.

The Stage 2 Project carried out instrumented field trials of the vehicle combinations similar to those identified as having performance deficiencies in the report titled "Stability and On-Road Performance of Multi-Combination Vehicles with Air Suspension Systems – Stage 1" [3]. The purpose of the field trials was to primarily validate or otherwise the computer simulations utilised in the Stage 1 project.

The following vehicle combinations were tested for the Stage 2 air suspension project:

- Triple livestock road train with air suspension throughout
- Triple livestock road train with air suspension (except for mechanical dollies)
- Triple livestock road train with mechanical suspension throughout.

These vehicles were laden with livestock to typical WA livestock haulage practice. The conduct, results and outcomes of these tests are documented in this report.

The following conclusions were drawn from the vehicle tests:

(1) The predictions of road train livestock triple combination behavioural issues determined from the Stage 1 report computer simulations were essentially confirmed in the test program, namely:

   a. The yaw/roll response of the combination to driver steering input is exaggerated at a relatively low dominant frequency

   b. This dominant frequency is increased very significantly with mechanical suspension, and such an increase greatly assists drivers; a worthwhile increase in this dominant frequency also occured when mechanical suspension dollies were used with the air-suspended trailers

   c. This change in dominant frequency is primarily related to suspension roll stiffness: the mechanical suspension tested was stiffer and increased the dominant frequency

   d. When the dominant yaw/roll response frequency is sufficiently higher than the driver's predominant steering frequency, exaggerated responses (swaying, yawing and rolling) of the rear unit are avoided and driver control is dramatically improved; this was achieved with the mechanical suspension tested on trailers and dollies; when the dollies only had mechanical suspension, there was also a worthwhile improvement in controllability of the combination.

(2) Further means of quantifying the performance of the combination vehicles with alternative suspension arrangements were also examined:

a. The yaw damping (a Performance Based Standards (PBS) vehicle measure) was relatively poor for the livestock triple combinations and the air-suspended test combination had the worst yaw damping

b. Yaw damping of all combinations tested was generally below current PBS recommendations; however, yaw damping is difficult to measure accurately in practice during on-road tests

c. The rearward amplification (a PBS vehicle measure) was slightly worse for the mechanically-suspended test combination; this measure was not particularly helpful in identifying steering control issues for the triple road trains

d. Two further PBS vehicle measures, Tracking Ability on a Straight Path (TASP) and High-Speed Transient Offtracking (HSTO) were examined using calibrated simulation models which confirmed that the air-suspended combination had worse performance than the mechanically-suspended combination; these measures also confirmed that the mechanical dollies had intermediate performance; the relatively small changes in these measures between vehicles/suspensions were not truly indicative of the driver-vehicle control differences which were measured during the tests.

e. The same roll steer coefficients were measured for all test vehicles; this implies that roll stiffness alone is a significant contributor to controllability of the vehicle combination; further investigation of roll steer coefficients is warranted.

f. The load distribution within axle groups of the test vehicles was generally satisfactory, was superior for the air suspensions, and it is considered that this did not affect the test results.

The following recommendations are provided in relation to the development of guidelines for suspensions used on heavy, high centre of gravity multi-combinations such as triple road trains carrying livestock:

(1) Guidelines for suspension use on triple road trains including those carrying livestock should be developed, taking into account:

a. The ability of mechanical suspension on trailers and dollies (as tested) to dramatically increase the controllability of such vehicle combinations

b. The ability of mechanically-suspended dollies to make a worthwhile contribution to the controllability of such combinations with air-suspended trailers

c. The contribution of air suspension to reducing road wear and to improving ride quality for the livestock; this should include consideration of the additional trailer sway and roll with air suspension and consequent effects on dynamic wheel loading and ride quality

(2) The development of guidelines for suspension use on triple road trains including those carrying livestock should be supported by:

a. Reasonable means of suspension classification which are acceptable to suspension manufacturers

b. Clear guidelines for suspension use based on safety performance of the triple combination

c. Practical means of defining combinations which are subject to the suspension recommendations

d. Consideration of the mass to be permitted on subject trailers when used in combinations other than triple road trains

e. Monitoring of the effectiveness of the guidelines, initially with operator surveys and with testing as required.

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1. INTRODUCTION

This project is based on the Terms of Reference (TOR) ‘Stability and On-Road Performance of Multi-Combination Vehicles With Air Suspension Systems’ agreed to at the Dubbo meeting of the Remote Areas Group (RAG) which was held on 19 February 2001.

The TOR provided for three stages of investigation. The three stages of investigation are collectively referred to as the Principal Project whilst the sub projects are referenced according to their respective stage numbers. This project is known as the “Stage 2 Project” and referred to in this manner throughout this document.

An increasing utilization of air suspension systems on heavy combination vehicles has occurred due to the implementation of higher mass limits under the national mass limits review conducted during 1993-1996[2] by the then National Road Transport Commission (NRTC) While this is a desirable outcome for productivity reasons, further work to provide guidance to operators and manufacturers in the best use and application of air suspension systems for various multi-combination vehicle configurations is considered necessary.

The primary areas of concern relate to multi-combination vehicles with air suspension systems that typically operate at high mass limits with high centre-of-gravity (COG) loads. There is strong anecdotal evidence that air suspension modifications on some vehicles are being undertaken to counteract some of the reported undesirable behaviours

Reported undesirable behaviours included increased roll, sway and lurch of the vehicle making it difficult for the driver to control the combination. Drivers also reported that air sprung prime movers had a tendency to follow road indentations requiring a greater steering effort to keep the vehicle on its intended path. Air suspended dollies were reported to increase roll, reduce stability and behave erratically under heavy braking.

As a result, drivers reported a preference for spring dollies that they felt were safer and considered their use resulted in a combination that was much easier to control.

A survey conducted by Estill and Associates [1] provided sufficient anecdotal evidence to make it apparent that guidelines for the use of air suspension systems in multi combination vehicles would be a positive safety initiative and of assistance to both manufacturers and operators alike.

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financed this report in conjunction with the NRTC. Some financial assistance was also received from industry groups within RAG. The completion of this report concluded Stage 1 of the RAG Air Suspension Project.

There was some strong feeling amongst certain RAG members, supported by the manager of the project, that the theoretical computer simulations should be confirmed by physical instrumented testing of multi-combinations. To this end, the WA Livestock Association, Main Roads (WA) and DPI (WA) agreed to finance the second stage of the Project. The National Transport Commission (NTC) agreed to assist DPI (WA) in the administration of the contract.

Roaduser Systems was commissioned to carry out Stage 2 of the project. In the course of preparations for the vehicle testing, an opportunity arose to combine the Stage 2 testing with a separate, but related project for Main Roads WA, which involved testing of the acceleration and deceleration performance of combination vehicles. Queensland Transport also decided to fund the testing of two further innovative combinations as part of the Stage 2 air suspension testing program.

The testing was carried out over a five day period between the 9th and 13th of April 2004 in Perth WA. A section of the Great Eastern Highway Bypass near Guilford was utilised by closing one side of the bypass to traffic using contra-flow traffic control. This resulted in the availability of approximately 3 km of high quality roadway of suitable width for carrying out dynamic manoeuvres (as well as acceleration and deceleration for the Main Roads WA project). The Stage 2 air suspension project also required the capture of data during normal driving, and a circuit adjacent to the bypass site was selected, approved and utilised for this purpose. The larger combinations required pilot vehicles when negotiating this circuit.

The test program was a major logistical exercise and the many elements of its organisation were co-ordinated by Main Roads WA, with input from DPI (WA) and all other participants.

As planned, the following vehicle combinations were tested for the Stage 2 air suspension project:

- Triple livestock road train with air suspension
- Triple livestock road train with air suspension (except for mechanical dollies)
- Triple livestock road train with mechanical suspension throughout.

These vehicles were laden with livestock to typical WA livestock haulage practice. The conduct, results and outcomes of these tests are documented in this report.

In addition, certain tests were carried out on a BAB-quad livestock combination which was included at the request of the participating livestock operator. The testing and computer simulation modelling carried out for this combination are documented in Appendix A.

The following innovative combinations were tested for Queensland Transport:

- A+A+B side tipper combination with air suspension, laden to: (i) standard national axle mass limits and (ii) concessional mass limits (as are available in WA)
- A+B3 container combination with mechanical suspension, nominally laden to standard national axle mass limits.

The results of these innovative vehicle tests have been reported separately to Queensland Transport. Queensland Transport has agreed to allow these results to be included in this report as further reference material and appear in Appendix A.

2. OBJECTIVES

2.1 Aims of Stage 2 Project

The Stage 2 Project carried out instrumented field trials of the vehicle combinations similar to those identified as having performance deficiencies in the report titled “Stability and On-Road Performance of Multi-Combination Vehicles with Air Suspension Systems – Stage 1” [3]. The purpose of the field trials was to primarily validate or otherwise the computer simulations utilised in the Stage 1 project. The trials also included assessment of the effectiveness of countermeasures to improve vehicle handling, in that the air-suspended triple was tested with both air-suspended dollies and with alternative mechanical dollies.

The Stage 1 Project identified that some multi-combination vehicles have performance deficiencies that are potentially serious. It was recommended that, as these conclusions were based on computer simulations, field trials should be carried out to confirm the key results of the study. The project manager was particularly concerned that since some of the key computer simulation findins introduced new concepts about the handling of large combination vehicles, it placed a greater necessity on the project team to seek validation of these results before presenting them as issues to be considered in heavy vehicle design and operation.

It was recommended that testing should encompass multi-combinations that exhibit satisfactory handling and units that are considered unsatisfactory. Two types of performance deficiency were highlighted: (i) high gain, low frequency yaw roll dynamics and (ii) tendancy to prime mover oversteering.

Test vehicles were high-COG, high mass, triple road train configurations. Vehicles included at least one triple stock road train with air suspension and a similar road train with mechanical suspension. All tests were conducted at approximately the same loaded mass, suitable for validating the computer simulations as required by the scope of this project.

The on-road test methods were capable of measuring:

- Driver steering input and frequency content
- Lateral acceleration output and frequency content
- Lateral acceleration gain through the frequency range 0 – 2 Hz

- Rearward amplification
- High-speed transient offtracking
- Yaw damping
- Roll angles and roll gradients of the rear trailer (and dolly) suspensions
- Roll steer coefficient of all suspension types used.

The testing and data analysis were designed to address:

- Confirmation and validation of the findings of Stage 1
- Identification of any limitations of the models (eg range of parameters/vehicle combinations)
- Determination of whether or not there are any variations from the original specification of the vehicle/vehicles, which could be employed to improve the handling characteristics of the combinations
- Comparison between the predicted behaviour from the Stage 1 Project and the observed behaviour from this Stage 2 Project and a definition of the proposed performance measure the model predicts
- Recommendations on the effectiveness of any countermeasures examined.

2.2 Constraints

Testing of combination vehicles involves certain practical constraints which mean that certain decisions need to be taken during testing which modify or vary some of the planned objectives and scope of the study.

The major areas of constraint for consideration with the Stage 2 air suspension project were:

- Available test site time
- Vehicle speeds attainable
- Safe speeds for lane change tests
- Site geometry
- Loading of vehicles.

The tests were carried out over the Easter holiday period in order to minimise traffic disruption to the public. While early starts and late finishes maximised the use of the test site, it was still necessary to escort the triples from the end of the test site back to the start of the test site, with difficult turns through traffic. Despite the best efforts of all concerned (traffic controllers, pilots and drivers) this was a time-consuming process, dependent on the amount of other traffic on the contra-flow bypass section. This limited the total number of runs which could be carried out and affected the number of repeat runs.

The site involved a slight down-grade (which assisted in increasing vehicle speed) followed by a slight up-grade. However, the higher mass vehicles had a variable ability to reach speeds of 80 km/h or above. While it was possible to undertake a “flying start” through the intersection at the start of the course (with the special assistance of traffic controllers and pilots) this required a longer turn-around loop to be undertaken, with further time penalties.

Safety considerations required the lane-change tests to commence at lower levels of severity and gradually increase in severity, subject to real-time monitoring of key indicators such as maximum roll angle of the rear trailer. The severity of the lane-change manoeuvre may be adjusted by reducing either the lateral deviation of the manoeuvre (which is 1.46 m in the standard SAE lane-change) or by reducing the vehicle speed from the standard speed of 88 km/h. Given the time constraints, and the fact that vehicle combinations varied in their speed capability, it was necessary to select a judicious sequence of lane-change tests which tended to be unique for each vehicle.

As mentioned, the test site contained both down-grade and up-grade sections, and the lane-change manoeuvres were carried out on the slight up-grade. There was also significant cross-fall throughout the section where the lane-changes were undertaken. Experience has shown that these departures from flat, level geometry significantly affect dynamic performance measured in lane-change manoeuvres. The most effective approach to relating the simulation model to the test data is to model the actual test conditions of speed, mass, geometry and steering input and compare this model output with the test measurements.

The livestock vehicles were loaded in a manner which represented typical practice by the operator who provided the test vehicle. As it turned out, the axle group and gross mass were slightly below standard national mass limits. The same group of cattle were used for all triple road train tests and therefore, in principle, the same payload mass was used on all three test vehicles. The cattle were unloaded at local sale yards each night and reloaded the following morning. Certain variations in mass of the beasts could occur due to changes in their condition over a period of days; also the mass of effluent in the trailers could vary from day to day.

Considering this range of constraints, it was decided to approach the confirmation and validation of the Stage 1 findings using the following process:

- Exercising simulation models for the actual test conditions (load, speed, site geometry, manoeuvre etc)
- Comparing the simulation model outputs to the test results
- Calibrating the models to the test results
- Using the calibrated models to quantify vehicle performance, compare vehicles and address the performance issues raised in Stage 1 of the project.

3. TEST PROGRAM

Test vehicles were organised by Mr Ian Tarling on behalf of DPI and were provided by Mitchell Livestock Transport and Leeds Transport. All combinations were conventional triple bottom configuration consisting of a 6x4 prime mover hauling three triaxle livestock semi-trailer and utilising two tandem dollies. The combinations varied in suspension types fitted, and utilised both air-suspended and mechanically-suspended semi-trailers and dollies. A typical load of livestock (cattle) was used for all three vehicles.

Vehicles were instrumented to meet the objectives of the test program. All pertinent vehicle specifications and dimensions were recorded. Vehicles were then loaded with livestock and weighed by Main Roads WA transport compliance unit officers who were experienced at weighing heavy vehicles. Each axle was weighed separately which provided additional useful data on load sharing in each axle group. Testing was then carried out, commencing with the route testing (which simulates normal driving) and moving on to stylised test manoeuvres such as lane changes.

3.1 Test vehicles

All test vehicles were of identical configuration and were selected to vary in suspension characteristics; this meant that certain design details of the semi-trailers, bodies and dollies also varied. Two combinations utilised the same prime mover and the same air-suspended trailers.

Dimensional drawings of each vehicle are shown in Figure 1, Figure 2 and Figure 3.

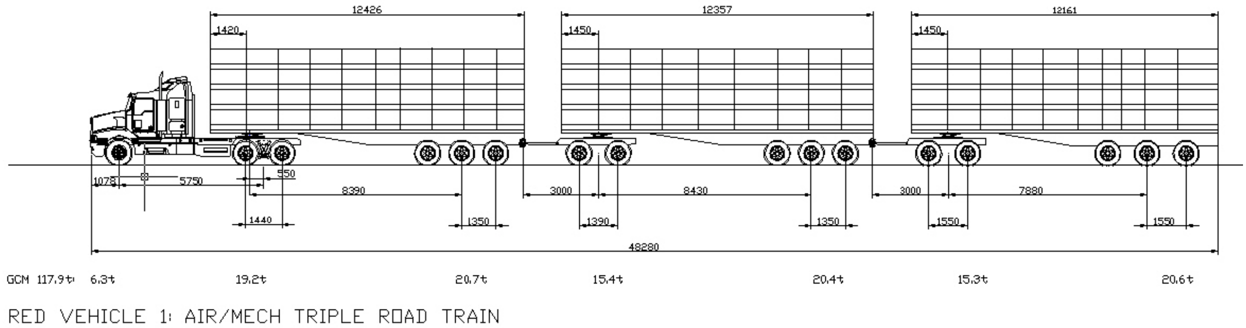


Figure 1. Vehicle 1 configuration

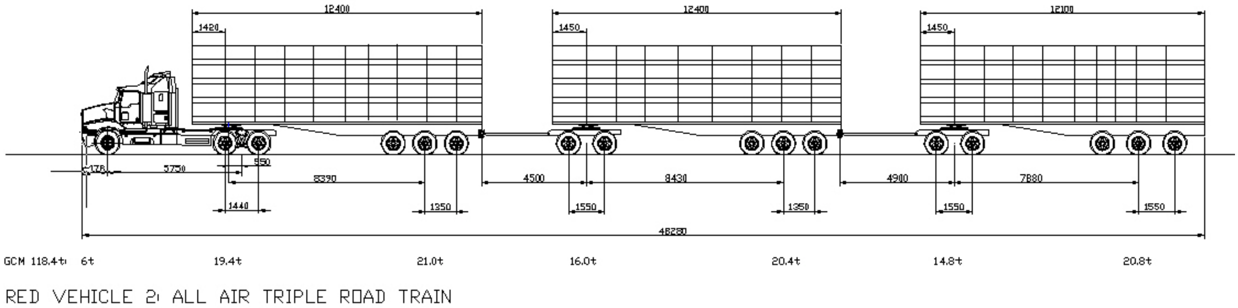


Figure 2. Vehicle 2 configuration

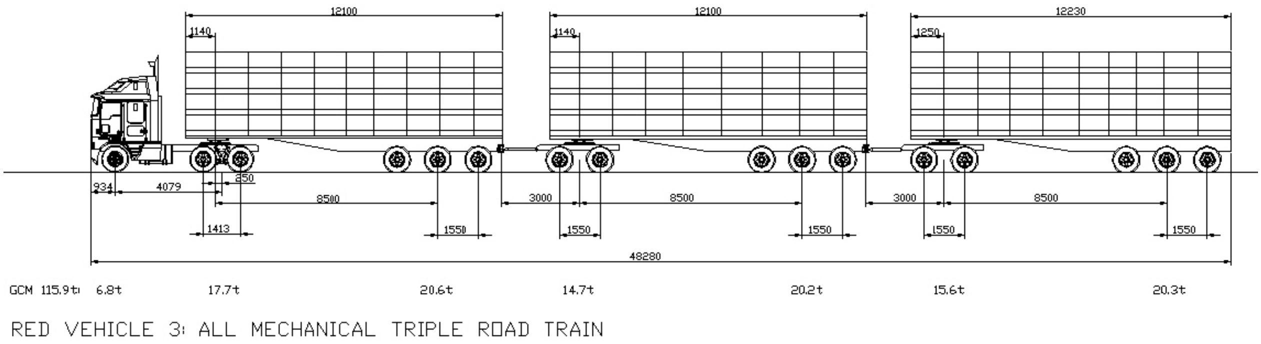


Figure 3. Vehicle 3 – configuration

3.1.1 Vehicle 1

Vehicle 1, from Mitchell Livestock Transport, comprised a Western Star conventional 6x4 prime mover (6-rod mechanical suspension) hauling three double deck triaxle livestock trailers (SFM) with BPW air suspension. The two tandem dollies were manufactured by DRTS and had 4-spring mechanical suspension. The vehicle combination is shown in Figure 4.

Figure 4. Vehicle 1 – air suspended trailers with mechanical dollies

Pertinent vehicle specifications were as follows:

Prime Mover

6x4 conventional cab Western Star Constellation 600 hp

6-rod mechanical suspension

steer tyres: 385/65R22.5 single

drive tyres: 315/80R22.5 duals

5.85 m wheelbase

Trailers

SFM triaxle trailers

BPW air suspension

11R22.5 dual tyres

12.2 m crate length

8.4 m s-dimension

Dollies

SFM/DRTS tandem dollies

4-spring mechanical suspension

11R22.5 dual tyres

3.00 m drawbar length

3.1.2 Vehicle 2

Vehicle 2, from Mitchell Livestock Transport, comprised a Western Star conventional 6x4 prime mover (6-rod mechanical suspension) hauling three double deck triaxle livestock trailers (SFM) with BPW air suspension. The two tandem dollies were manufactured by DRTS and had BPW air suspension. The vehicle combination is shown in Figure 5.

Figure 5. Vehicle 2 - all air suspension

Pertinent vehicle specifications were as follows:

Prime Mover

6x4 conventional cab Western Star Constellation 600 hp

6-rod mechanical suspension

steer tyres: 385/65R22.5 single

drive tyres: 315/80R22.5 duals

5.85 m wheelbase

Trailers

SFM triaxle trailers

BPW air suspension

11R22.5 dual tyres

12.2 m crate length

8.4 m s-dimension

Dollies

SFM tandem dollies

BPW air suspension

11R22.5 dual tyres

4.5 m and 5.0 m drawbar lengths

3.1.3 Vehicle 3

Vehicle 3, from Leeds Transport, comprised a Kenworth K104 COE 6x4 prime mover (6-rod mechanical suspension) hauling three double deck triaxle livestock trailers (SFM) with mechanical suspension. The two tandem dollies were manufactured by SFM and had 4-spring mechanical suspension. The vehicle combination is shown in Figure 6.

Figure 6. Vehicle 3 – all mechanical suspension

Pertinent vehicle specifications were as follows:

Prime Mover

6x4 COE Kenworth K104 645 hp

6-rod mechanical suspension

steer tyres: 11R22.5 single

drive tyres: 11R22.5 duals

4.00 m wheelbase

Trailers

SFM triaxle trailers

6-spring mechanical suspension

11R22.5 dual tyres

12.2 m crate length

8.4 m s-dimension

Dollies

SFM tandem dollies

4-spring mechanical suspension

11R22.5 dual tyres

3.00 m drawbar length

3.1.4 Loading and axle weights

The same load of cattle was used for all three test vehicles. Table 1 shows the axle group and Gross Combination Mass (GCM) conditions for each of the three test vehicles. It is apparent that GCMs were all similar, in the range 115.9 – 118.4 t.

Table 1. Axle group weights and GCM by test vehicle

Vehicle	**Axle group load (t)**							**GCM (t)**
	Steer	**Drive**	**T1**	**Dolly**	**T2**	**Dolly**	**T3**	
Vehicle 1 *(air/mech dollies)*	6.3	19.2	20.7	15.4	20.4	15.3	20.6	**117.9**
Vehicle 2 *(all air)*	6.0	19.4	21.0	16.0	20.4	14.8	20.8	**118.4**
Vehicle 3 *(all mech)*	6.8	17.7	20.6	14.7	20.2	15.6	20.3	**115.9**

Since the vehicle loading was measured using portable scales, it was possible to determine individual axle loads within each axle group. This provided information on any load skew (ie. improper static load sharing) within the groups. The axle loads listed in Table 1 are split into individual axle loads in Table 2. Small amounts of load skew can be observed in some of the axle group loads, but axle group loads are generally quite well shared between axles. This is particularly true for the air-suspended trailers, where load sharing is within 1 – 2%. The mechanically-suspended trailers demonstrate load sharing within 8% (worst case).

The GCM of the vehicles tested differed by 2.5 tonnes between the all-air suspension vehicle (118.4 t) and the all-mechanical suspension vehicle (115.9 t). This difference is not shared evenly across the axle groups of the combinations, with the greatest discrepancies in axle weights being at the forward half of the combination. The difference in rear-most trailer axle loads was 0.5 t with the highest load being recorded for the all-air suspension. The difference in the rear-most dolly axle group loads was 0.8 t with the highest load being recorded for the all-mechanical suspension vehicle (refer table 1). The test weights were very similar to the standard weights used for vehicle simulation.

Table 2. Individual axle loads by test vehicle

Vehicle	Axle load (t)															
	St.	Drive		Trailer 1			Dolly		Trailer 2			Dolly		Trailer 3		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	6.3	9.7	9.5	7.0	6.8	6.9	7.4	8.0	6.9	6.7	6.8	7.9	7.4	6.8	6.9	6.9
2	6.0	9.9	9.5	7.0	7.1	6.9	8.5	7.5	6.7	6.9	6.8	7.6	7.2	6.8	7.0	7.0
3	6.8	9.0	8.7	7.4	6.8	6.4	7.5	7.2	6.9	6.6	6.7	7.9	7.7	6.5	6.8	7.0

3.2 Test site

The test site was located near Perth Airport on a designated section of the Great Eastern Highway Bypass. The test site was chosen by Main Roads WA, based upon its suitability for testing multi-combination vehicles with safety being the utmost priority. After each test run, vehicles completed a u-turn at the Abernathy Rd intersection and were directed to Kalamunda Rd and the Great Eastern Hwy, under the escort of pilot vehicles, before rejoining the Great Eastern Hwy Bypass. Figure 7 shows a map of the test site.

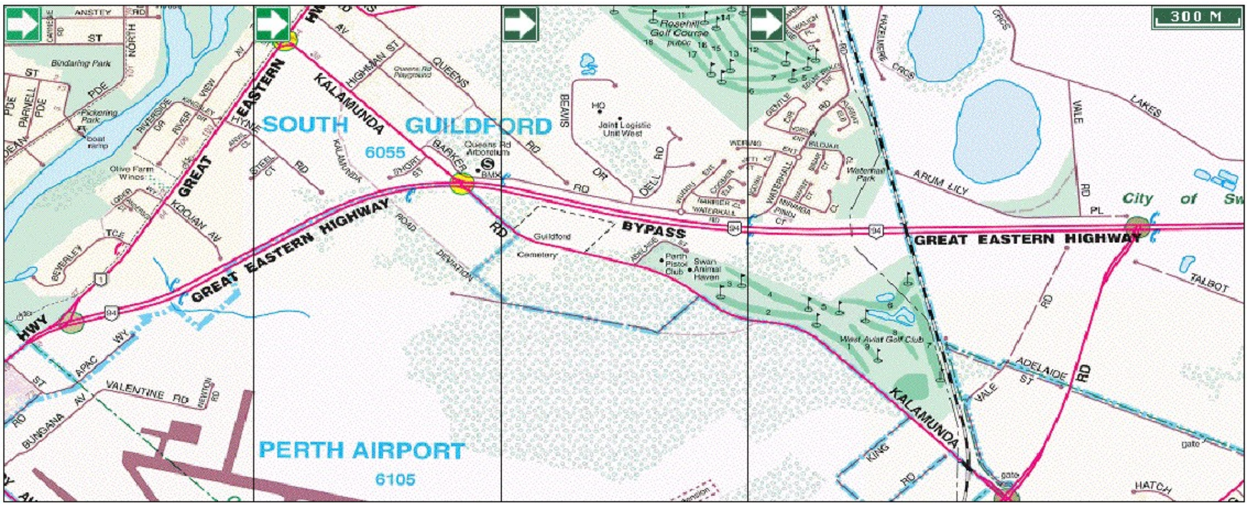


Figure 7. Map of Great Eastern Highway Bypass test site

Figure 8 shows the layout of the test area. Traffic controllers were positioned at the Kalamunda Rd intersection and the Abernathy Rd intersection.

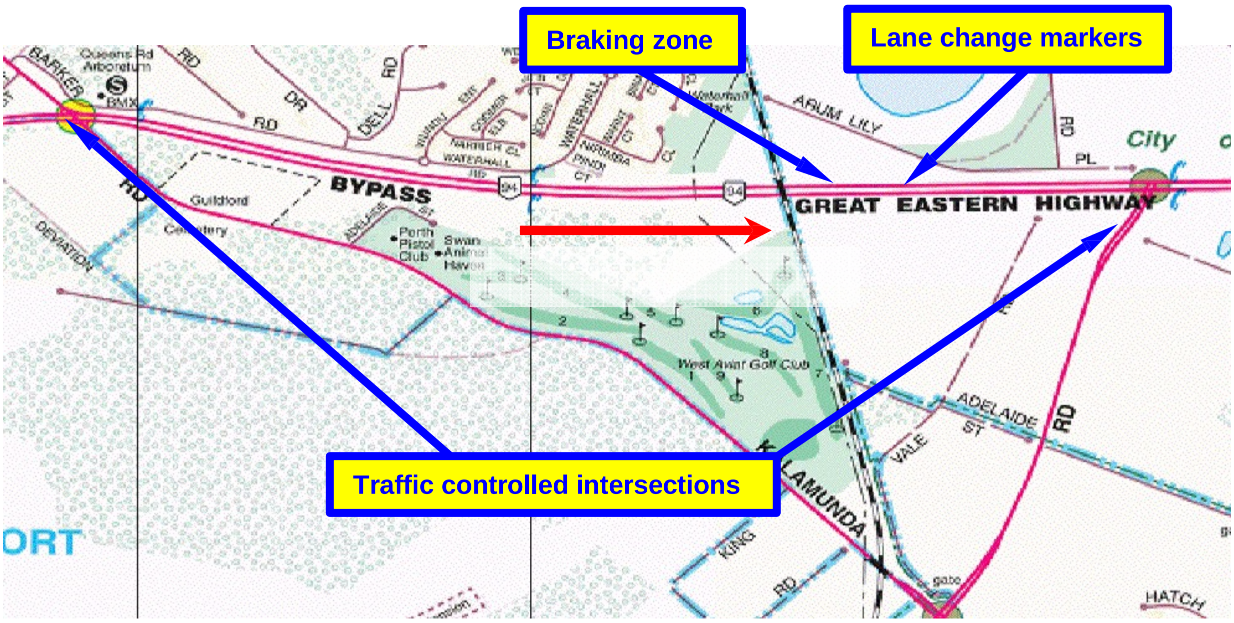


Figure 8. Layout of test site

Figure 9 is a photo taken from the cabin of a test vehicle as it entered the lane change testing area. Pink and yellow markers on the road clearly show the path the driver was asked to follow to successfully complete a lane change maneouvre. The yellow markers indicate the standard SAE lane change path [2]. The pink markers indicate 60% of the full width lane change, as used for all triple road train test vehicles.

Figure 9. Driver's view of Great Eastern Highway Bypass test site

Route testing was completed over a 25 km circuit including the Roe Hwy, Tonkin Hwy, Kewdale Rd and Abernathy Road. This circuit took typically 30 minutes to complete under the escort of pilot vehicles.

3.3 Vehicle instrumentation

Each test vehicle was fitted with the following instrumentation:

- Accelerometers to measure lateral acceleration
- Yaw rate sensor – yaw rate is the angular velocity about a vertical axis
- Axle-chassis vertical displacement on both sides of the rear axle – the relative displacement, together with the lateral spacing between the sensors, provides the axle-chassis roll angle
- Axle-chassis longitudinal displacement on both sides of the rear axle – the relative displacement, together with the lateral spacing between the sensors, provides the axle-chassis steer angle
- Front wheel steering angle – this is required for the handling measure
- GPS vehicle speed and position.

Figure 10 shows a sensor junction box fitted to the dolly of the triple roadtrain. Multi-core data cables ran the length of the vehicle between the local junction boxes and the data acquisition unit situated in the cabin of the prime mover. Single channel data cables ran from individual sensors to their local junction box.

Figure 10. Instrumentation on dolly of livestock road train

Figure 11 shows the two linear displacement transducers fitted to the rear suspension of the rear-most unit of a triple road train combination. The sensor shown in Figure 11 measured the longitudinal displacement of the rear axle. Figure 12 shows one of the sensors fitted to the prime mover to measure acceleration in the longitudinal direction. The prime mover was also fitted with a lateral accelerometer, yaw rate sensors and steering angle sensor.

Figure 11. LDT fitted to trailer suspension

Figure 12. Accelerometer on prime mover

Figure 13 is a typical screen capture of the data acquisition software graphical user interface used by the vehicle testing engineer.

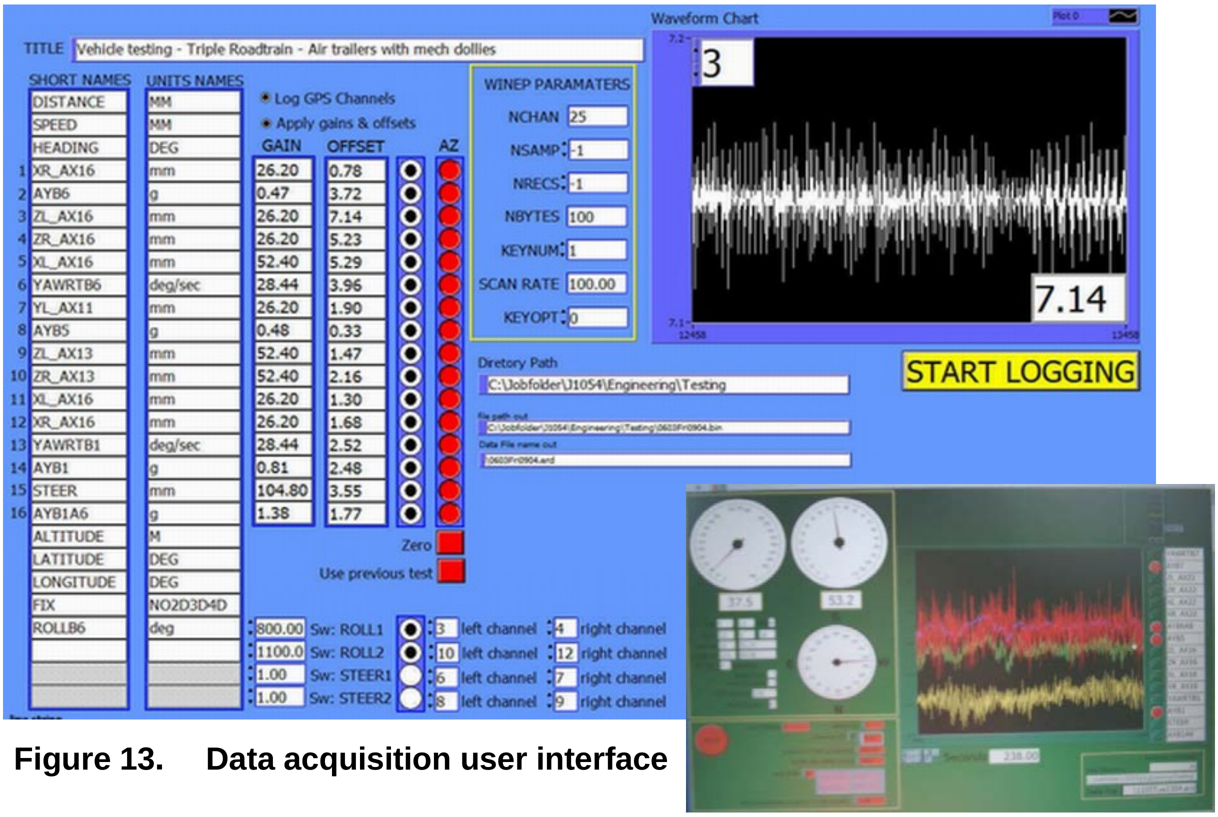


Figure 13. Data acquisition user interface

3.4 Test procedure

3.4.1 Preparation and procedures followed

Mr Ian Tarling was engaged by DPI to assist with sourcing and co-ordinating test vehicles, loads and drivers and to recommend facilities where vehicle instrumentation, hook-up and loading could take place. Ian Tarling also provided pertinent information to Main Roads WA for the issue of permits to move vehicle combinations larger than double road trains.

All test manoeuvres for all vehicles were pre-screened using RATED simulation models to ensure that the vehicles could perform the manoeuvres with an appropriate safety margin. In particular, the lateral displacement of the lane-change manoeuvre was set using RATED models to an initial value of 60 % of the full SAE lane-change.

With the assistance of Main Roads WA transport compliance unit personnel, all test vehicles were visually inspected for mechanical defects prior to testing. Axle, axle group and gross weights were obtained by Main Roads WA personnel, using portable scales, prior to testing.

Traffic control was designed and managed by Main Roads WA who also engaged pilots for escorting triple road trains when required to travel off the closed bypass section.

Drivers were instructed that the purpose of the testing was to exercise the vehicle well within its safe manoeuvring range. All vehicle combinations were driven by their regular drivers. Test results were monitored progressively to ensure that vehicle responses remained within safe limits.

A Roaduser test engineer travelled in the cabin at all times and was in radio contact with the test director.

3.4.2 Test sequence

The following sequence was carried out for each of the three livestock triples tested:

- The appropriate vehicle configuration was assembled at a local transport yard (as per arrangements made by Ian Tarling) the day prior to the testing
- The prime mover and trailer were instrumented at the transport yard the day prior to the testing
- On the test day, the vehicle was moved to the saleyards under escort and cattle were loaded
- The vehicle was moved under escort to the bypass site and was weighed and inspected by Main Roads WA personnel
- The vehicle then departed under escort to carry out the pre-arranged circuit of normal driving on a selected and approved route; this circuit was usually completed twice

- Lateral stability tests were carried out at the closed bypass site; these tests included lane-changes (from a range of speeds and with varying lateral deviation) and yaw damping manoeuvres.

4. DATA ANALYSIS

4.1 Normal driving

4.1.1 Steering amplitude

Normal driving tests were conducted over the specified open road circuit. The data traces shown in Figure 14, Figure 15 and Figure 16 represent the entirety of the 30 minutes of data logged for each vehicle over the 25 km open road circuit.

Figure 14 shows the data trace of the driver steering input for the air suspension with mechanical dollies combination (Vehicle 1).

Figure 15 shows the data trace of the driver steering input for the all-air-suspended triple road train (Vehicle 2).

There are four noticeable peaks common to all data traces; these are the turns made at major intersections during the circuit. The two peaks of greatest magnitude occurring at the mid point of the data trace are (i) a right turn on to the Tonkin Hwy (ii) a left turn at Abernethy Rd. The major turns do not occur at the same times for the two circuits. This is due to the fact that traffic conditions, light signals etc differ between each circuit. The magnitudes of each peak are, however, very similar. This indicates that the driver took basically the same approach to negotiate the turns for both combinations. These events are low speed events and were not expected to provide significant information regarding the behaviour of different suspension types.

When a comparison between the two steering input data traces for the air suspension with mechanical dollies combination (Figure 14) and the all-air-suspension vehicle (Figure 15) is made, the difference between the two becomes visually apparent. The perceptible difference is that the straight line data centred around zero is much broader for Vehicle 2 than it is for Vehicle 1. This “broad” centre line appears as a single solid line but in fact represents the amplitude of the numerous repeated oscillations of the steering wheel. These repeated oscillations are the corrections that the driver was continually making to the steering wheel whilst tracking in a straight line. The fact that the centre line appears broader for the all air suspension combination means that the driver was in fact making much larger corrections to the steering wheel i.e. the driver was working harder at the wheel when driving the all-air-suspended vehicle.

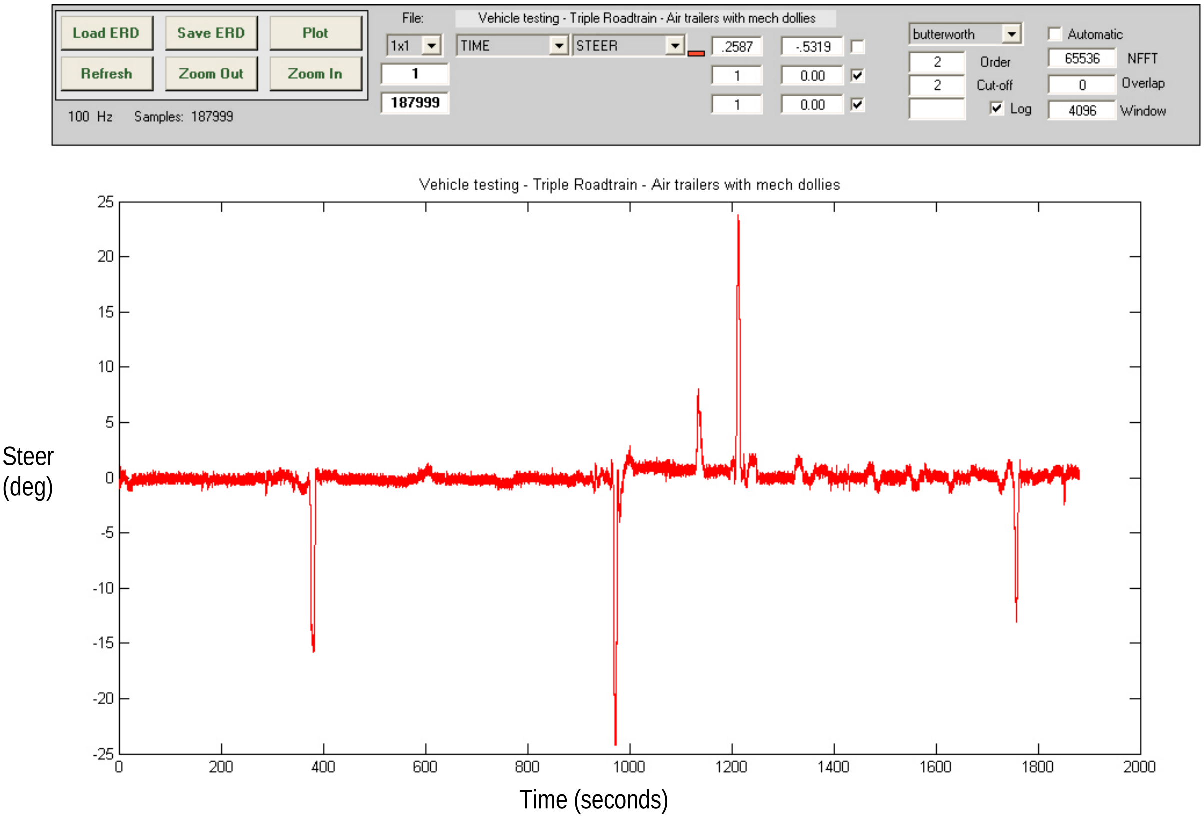


Figure 14. Air suspension with mechanical dollies - driver steering input

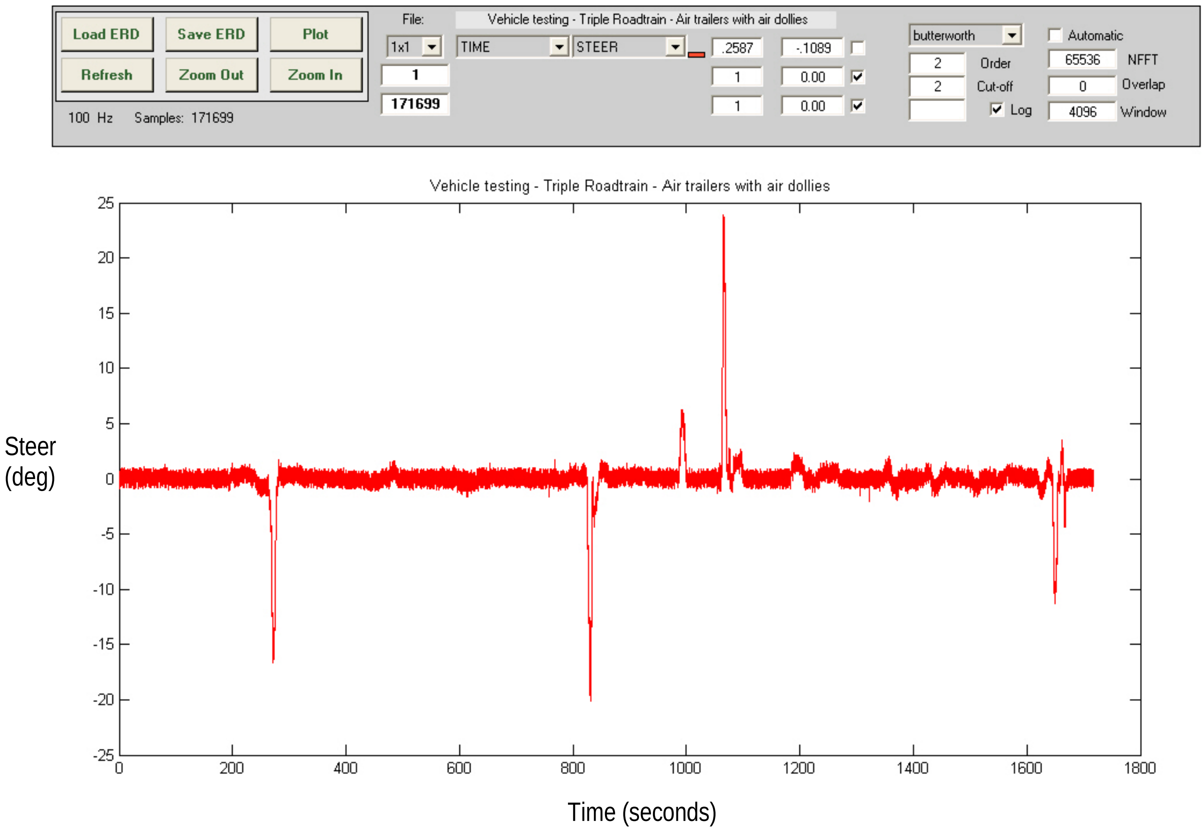


Figure 15. All air suspension - driver steering input

Figure 14 and Figure 15 are directly comparable as the same driver and prime mover was used for both combinations. Vehicle 3 was an all-mechanical-suspension triple road train, with a different driver and prime mover. The driver steering input for Vehicle 3 is shown in Figure 16. Comparison between the previous steering data and that of Vehicle 3 needs to consider variations due to driver habit/technique and prime mover handling characteristics.

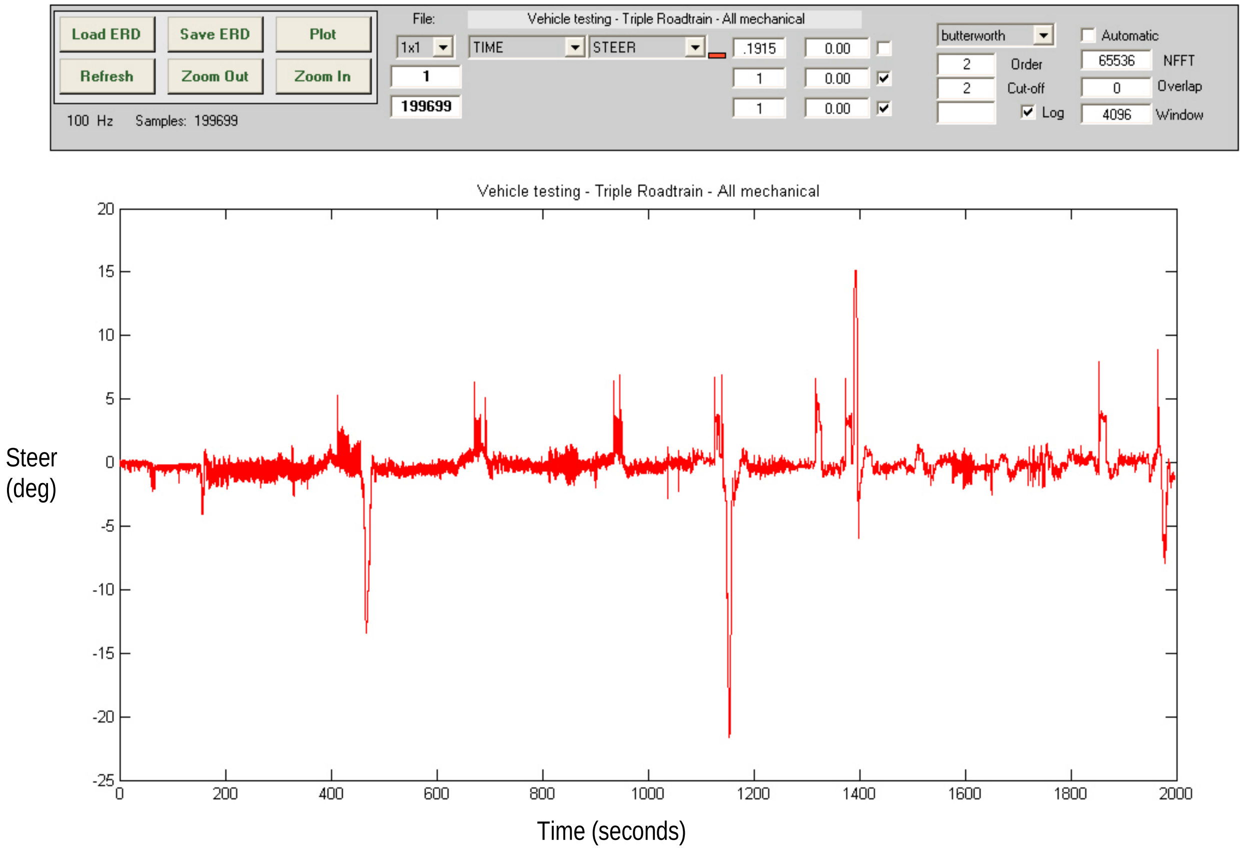


Figure 16. All mechanical suspension - driver steering input

The data trace of the all-mechanical combination shows variations in the amplitude of the steering input across the entire route. These were due to the fact that the driver was asked to carry out a number of steering manoeuvres whilst on the test circuit not asked during the trial of the previous combinations. This was done because of the better handling performance of the vehicle and the greater confidence in the vehicle’s ability to perform these manoeuvres safely on a public road. Whilst these manoeuvres were useful for data collection purposes, they nonetheless make visual comparisons between the driver steering input trace of Vehicle 3 and that of Vehicles 1 and 2 more difficult to interpret.

Statistical analysis was completed on matching sections of data to provide a fair comparison of the magnitude of driver steering input across the three vehicles. The sections of data selected were periods during the circuit where the vehicle was tracking straight, predominantly at higher speeds (subject to the local speed limit).

Table 3 is a summary of the RMS values of steering input over these sections. The higher the RMS value, the harder the driver was working at the wheel during this period. Table 3 clearly shows that the highest RMS values were recorded for the all-air-suspension vehicle (Vehicle 2). This supports the initial visual assessment of the data traces. The all-mechanical-suspension vehicle (Vehicle 3) is the next highest, with RMS value being equal to that of Vehicle 1 over the Roe Hwy section. It should be noted that RMS values will be affected by driver habit/technique when making comparisons with Vehicle 3 results.

Table 3. RMS of steering input by vehicle type and test location

Vehicle No.	Suspension	File	RMS steer angle comparison			
			GEHB* (deg)	GEHB* (%)	Roe Hwy (deg)	Roe Hwy (%)
1	Air trailers with mech dollies	703Fri0904	0.16 deg	73%	0.25 deg	83%
2	All air suspension	731Sat1004	0.22 deg	100%	0.30 deg	100%
3	All mechanical suspension	800Sun110 4	0.18 deg	82%	0.25 deg	83%

GEHB = Great Eastern Highway Bypass

4.1.2 Amplitude of vehicle motion variables

Further analysis was made of RMS values of data logged during the lead-up section approaching the lane change manoeuvre area. The data logged during this period on this section of road provided a good platform for comparison between the three vehicles. The data analysed over this period included the following relevant measures for assessment of vehicle stability and control:

- Yaw rate of the rear trailer unit (YawB6)
- Roll angle of the rear trailer unit (RollB6)
- Lateral acceleration of the prime mover (AYB1)
- Lateral acceleration of the rear trailer unit (AYB6)

Note that “B1” and “B6” in the annotation used to describe the logged data channels refer, respectively, to “Body 1” which is the prime mover and “Body 6” which is the rear trailer unit.

Table 4 includes RMS values for steering input (Steer), yaw rate of the rear trailer (YawB6), roll angle of rear trailer (Ro llB6), and lateral acceleration of the prime mover (AYB1) and the rear trailer (AYB6), as well as the maximum speed recorded during this period. It is apparent that:

- The all-air-suspended triple road train had the worst performance on all measures shown
- The all-mechanically-suspended road train had the best performance on all measures shown (except steering angle).

Table 4. RMS values during lane change lead up

Vehicle No.	1	2	3
Susp. type	Air trailers / mech dollies	All air suspension	All mechanical suspension
File 918Fri0904		927Sat1004	949Sun1104
Speed (max)	82.3 km/h	78.0 km/h	86.0 km/h
RMS Steer (deg)	0.123 (73%)	0.168 (100%)	0.144 (86%)
RMS YawB6 (deg/s)	1.03 (79%)	1.31 (100%)	0.50 (38%)
RMS RollB6 (deg)	0.110 (75%)	0.146 (100%)	0.041 (28%)
RMS AYB1 (g)	0.011 (79%)	0.014 (100%)	0.010 (71%)
RMS AYB6 (g)	0.024 (56%)	0.043 (100%)	0.023 (53%)

4.1.3 Steering and vehicle frequency characteristics

A frequency analysis of driver steering input was conducted for the data acquired during route testing. Figure 17 shows the power spectral density plot of steering input for each vehicle. The data collected over route testing contains numerous frequencies. A dominant peak is evident in each of the data traces. These peaks represent the dominant frequency at which the driver was operating. These dominant frequencies are those imposed on the driver by the vehicle, they should not be confused with the driver's 'comfortable' generally preferred steering frequency.

The dominant frequency for the all-air-suspension was 0.3 Hz. The dominant frequency for the all mechanical vehicle was at a lower 0.2 – 0.3 Hz range. For the air suspension with mechanical dollies vehicle the dominant frequency occured at 0.3 – 0.4 Hz.

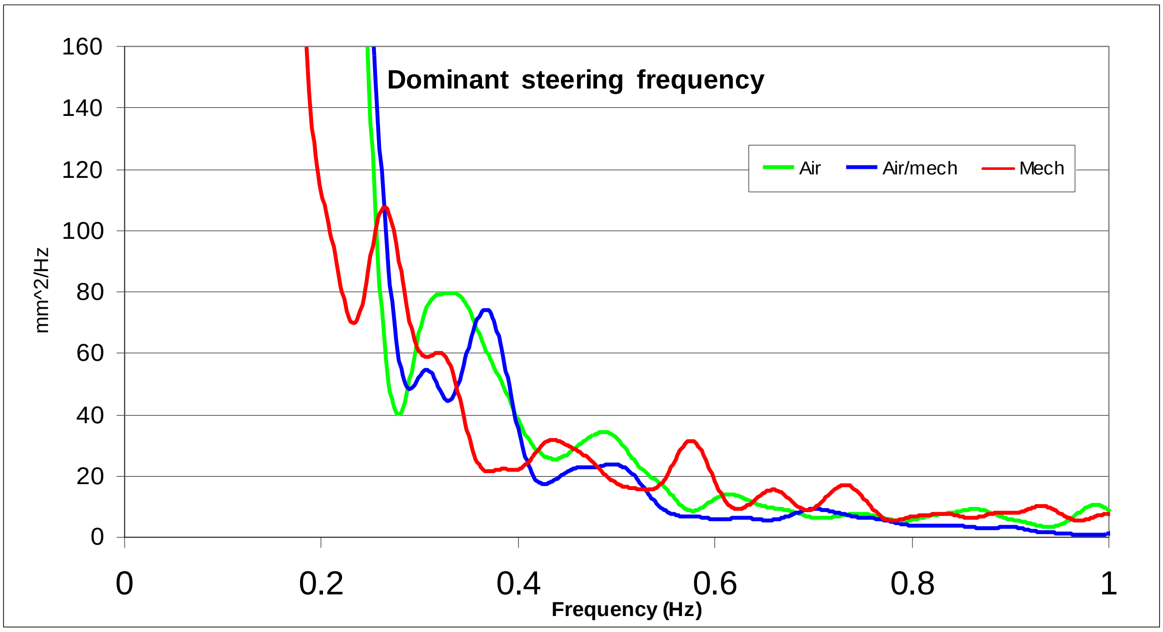


Figure 17. Power spectral density of steering input by vehicle

The transfer function between the lateral acceleration occurring at the prime mover and lateral acceleration occurring at the rear trailer was used to produce the frequency response for each vehicle. The frequency response (Figure 18) shows that the all-air-suspension vehicle peak gain occurs at 0.3 Hz, the all-mechanical suspension peak gain occurs in the range 0.5 Hz to 0.6 Hz, and the air suspension with mechanical dollies vehicle has peak gain occuring in the range 0.3 to 0.4 Hz. This is a highly significant difference in frequency response, and shows that the mechanically-suspended road train has a much higher dominant frequency than the two road trains with air suspension. It should also be noted that the dominant frequencies of the two triple road trains with air-suspended trailers produce extremely high rearward amplification ratios (in excess of 25:1), while that of the mechanically-suspended road train is significantly lower (20:1), but still relatively high. These high ratios illustrate the stability-and-control challenges facing road train drivers.

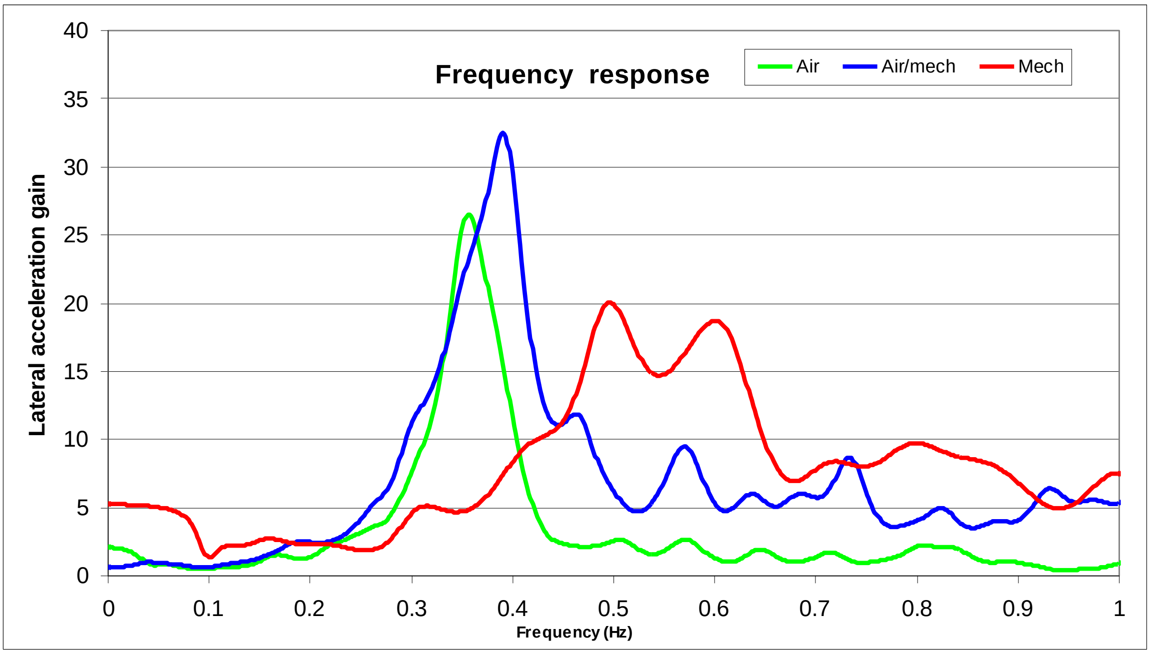


Figure 18. Frequency response (lateral acceleration) by vehicle

4.2 Lane-change manoeuvre

Stylised manoeuvre tests were conducted based on an adaptation of the SAE J2179 lane change manoeuvre. Road markers defined a path which the driver was instructed to follow whilst travelling at higher speeds (70 – 90 km/h). The safe and most suitable lane change manoeuvre path selected for these tests was a 60 % reduction of the J2179 manoeuvre, which has a lateral offset of 0.9 m (instead of the standard 1.46 m). Two consecutive lane change manoeuvres were marked out on road, therefore allowing two lane change manoeuvres to be completed per run. The first lane change is referred to as “A” and the second as “B” (eg. LC 1B in Table 5) . Table 5 summarises the results of each run. The peak values of lateral acceleration for the prime mover (AYB1) and the rear trailer (AYB6) were used to calculate the rearward amplification (RA). The speed at which the manoeuvre was conducted has been included for each run.

Table 5. Vehicle 1 lane change manoeuvre summary

Vehicle	File Test		AYB1 (g) (max)	AYB6 (g) (max)	V (km/h)	RA
1	0812Fri0904	LC 1A (60%)	0.06	0.23	79.8	3.6
1	0812Fri0904	LC 1B (60%)	-0.05	-0.12	79.6	2.4
1	0854Fri0904	LC 2A (60%)	0.04	-[3]	82.1	-
1	0854Fri0904	LC 2B (60%)	-0.6	-	81.1	-
1	0918Fri0904	LC 3A (60%)	0.07	0.19	82.3	2.8
1	0918Fri0904	LC 3B (60%)	-0.08	-0.15	81.5	2.0
1	LC A Average		0.07	0.21	81.4	3.2
1	LC B Average		0.06	0.14	80.7	2.2
1 Overall	Average		0.07	0.17	81.1	2.7

[3] Clear peaks were not identifiable to record AYB6 for run 2 due to noise interefence.

Figure 19 shows the data trace of Vehicle 1 – Air/Mechanical triple roadtrain – File: 0918Fri0904. The lateral acceleration at the prime mover (AYB1) is shown in red and the rear trailer (AYB6) is shown in blue.

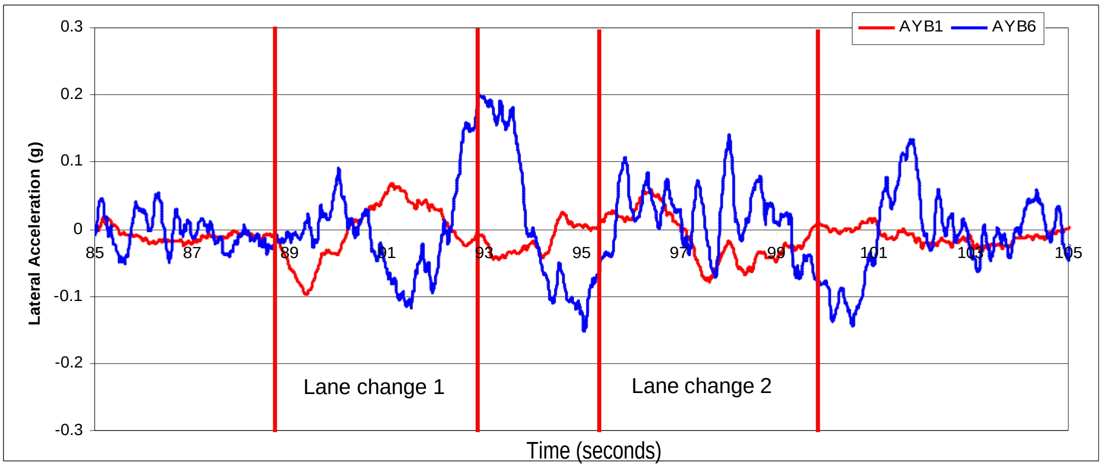


Figure 19. Lane change manoeuvre 1 -0918Fri0904

Figure 20 includes three data traces for Vehicle 1 – Air/Mechanical triple roadtrain – File: 0918Fri0904. The data traces shown in Figure 20 include data over the 120 second period from the first traffic control area to the completion of the lane change manoeuvre. The top diagram shows lateral acceleration, the middle diagram shows speed and the bottom diagram shows roll angle of the rear trailer.

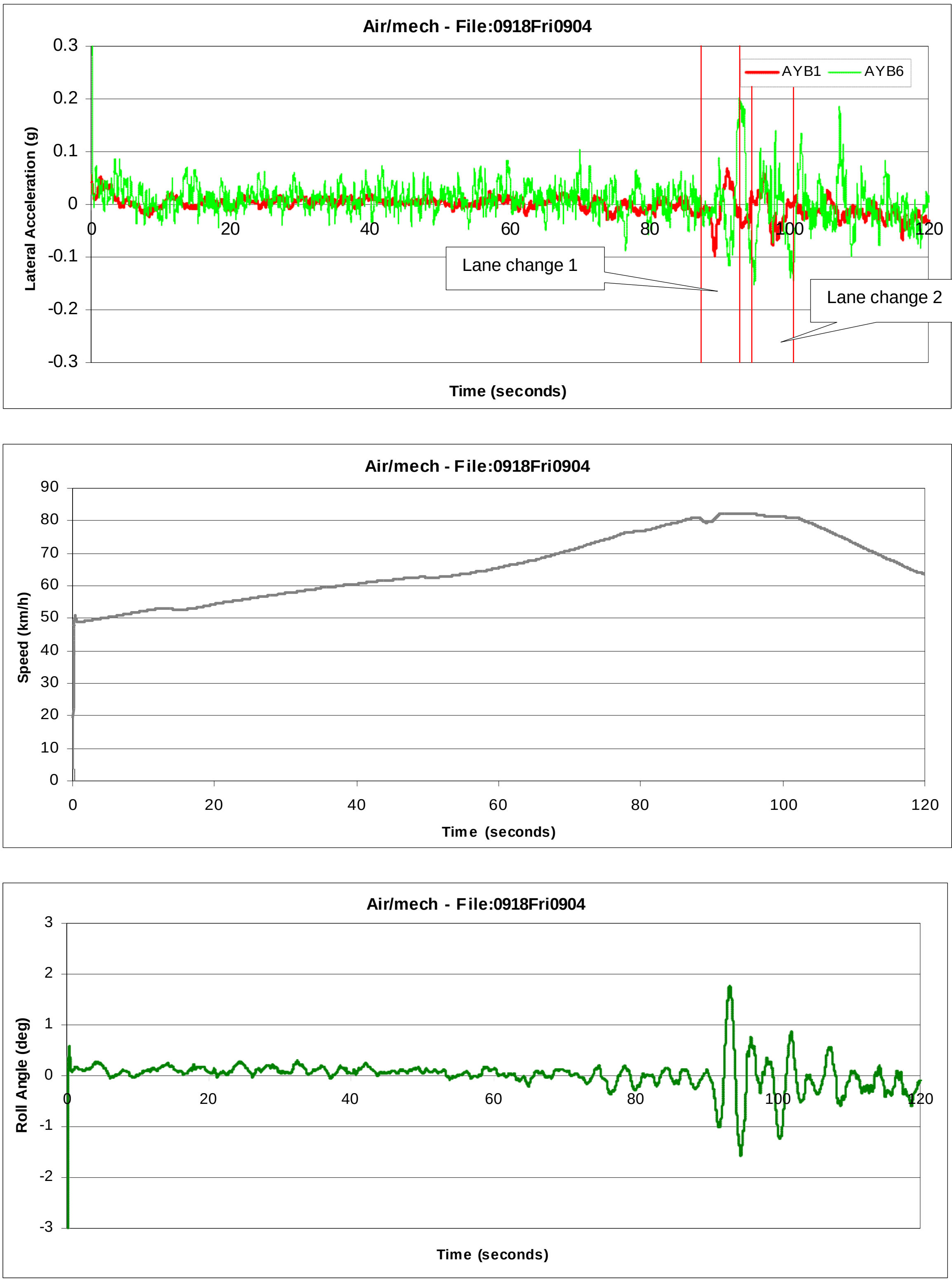


Figure 20. Lane change maneovure -0918Fri0904

Table 6 is a summary of the peak val ues during each lane chang e manoeuvre for Vehicle 2 – All air suspension triple roadtrain.

Table 6. Vehicle 2 Lane change manoeuvre summary

Vehicl e	File Test		AYB1 (g) (max)	AYB6 (g) (max)	V (km/h)	RA
2	0844Sat1004	LC 1A (60%)	0.037	0.14	72.2	3.8
2	0844Sat1004	LC 1B (60%)	0.056	0.146	68.5	2.6
2	0906Sat1004	LC 2A (60%)	0.083	.2475	78.9	3.0
2	0906Sat1004	LC 2B (60%)	-0.093	-.242	77.1	2.6
2	0927Sat1004	LC 3A (60%)	0.072	0.192	78.0	2.7
2	0927Sat1004	LC 3B (60%)	-0.132	-.294	73.4	2.2
2	LC A Average		0.064	0.193	76.4	3.2
2	LC B Average		0.094	0.227	73.0	2.5
2 Total	Average		0.079	0.210	74.7	2.8

Figure 21 shows the data trace of Vehicle 2 – All air sus pension triple road train – File: 09 27Sat1004. The lateral accelera tion at the p rime mover (AYB1) is shown in red and rear trailer (AYB6) is shown in blue.

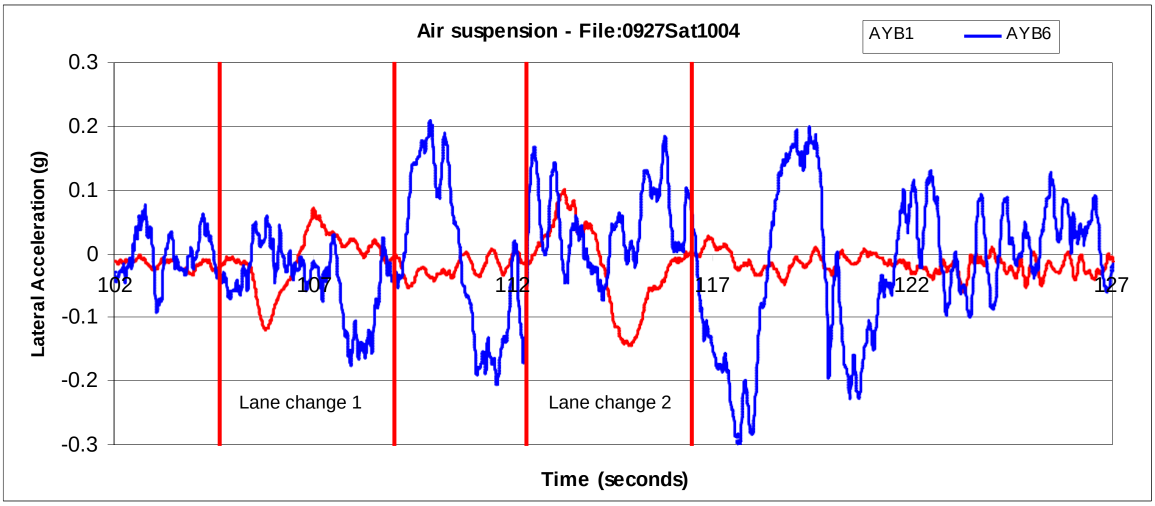


Figure 21. Vehicle 2 Lane change manoeuvre 0927Sat1004

Figure 22 includes three data traces for Vehicle 2 – All air suspension triple roadtrain File: 0927Sat1004. The data traces shown in Figure 22 include data over the 140 second period from prior to the first traffic control point to the completion of the lane change manoeuvre. The top diagram shows lateral acceleration, the middle diagram shows speed and the bottom diagram shows roll angle of the rear trailer.

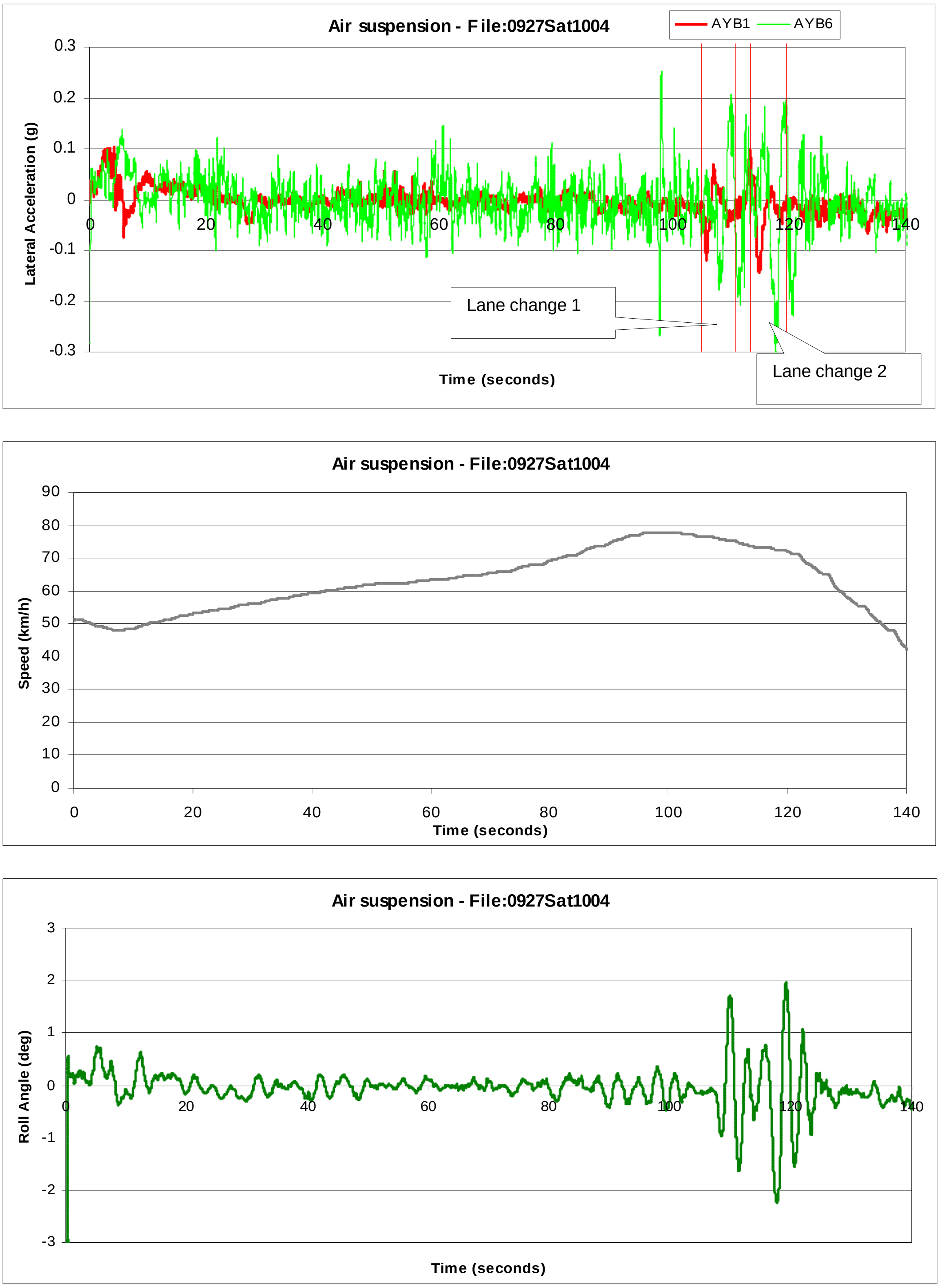


Figure 22. Vehicle 2 Lane change manoeuvre 0927Sat1004

Table 7 is a summary of the peak val ues during each lane change manoeuv re for Vehicle 3 – All mechanical suspension triple roadtrain.

Table 7. Vehicle 3 Lane change manoeuvre summary

Vehicle	File Test		AYB1 (max) (g)	AYB6 (max) (g)	V (km/h)	RA
3	0934Sun1104	LC 1A (60%)	.054	.17	77.2	3.14
3	0934Sun1104	LC 1B (60%)	-.085	-.155	75.2	1.8
3	0949Sun1104	LC 2A (60%)	.066	.17	86.0	2.6
3	0949Sun1104	LC 2B (60%)	-.057	-.19	84.7	3.3
3	1001Sun1104	LC 3A (60%)	.061	.192	85.0	3.1
3	1001Sun1104	LC 3B (60%)	.05	.223	82.5	4.5
3	LC A Average		0.060	0.177	82.7	2.9
3	LC B Average		0.064	0.189	80.8	3.2
3 Total	Average		0.062	0.183	81.8	3.1

Figure 23 shows the data trac e of Vehicle 3 – All mech anical s uspension triple roadtrain for lane c hange manoeuvre number 3 – File: 0949Sun1104. The lat eral acceleration at the prime mover (AYB1) is shown in r ed and rea r trailer (AYB6) is shown in blue.

[4] First lane change inaccurate steering input

Lane change 1

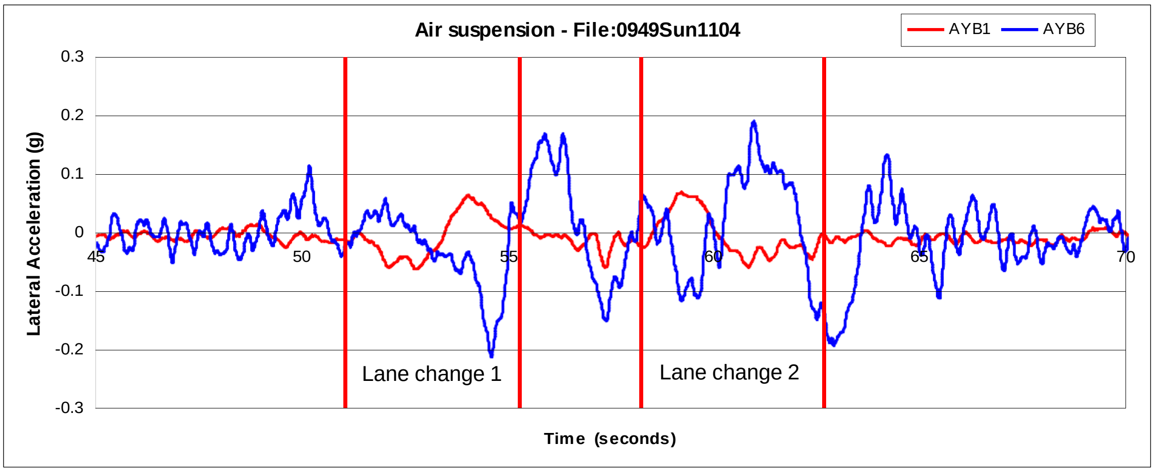
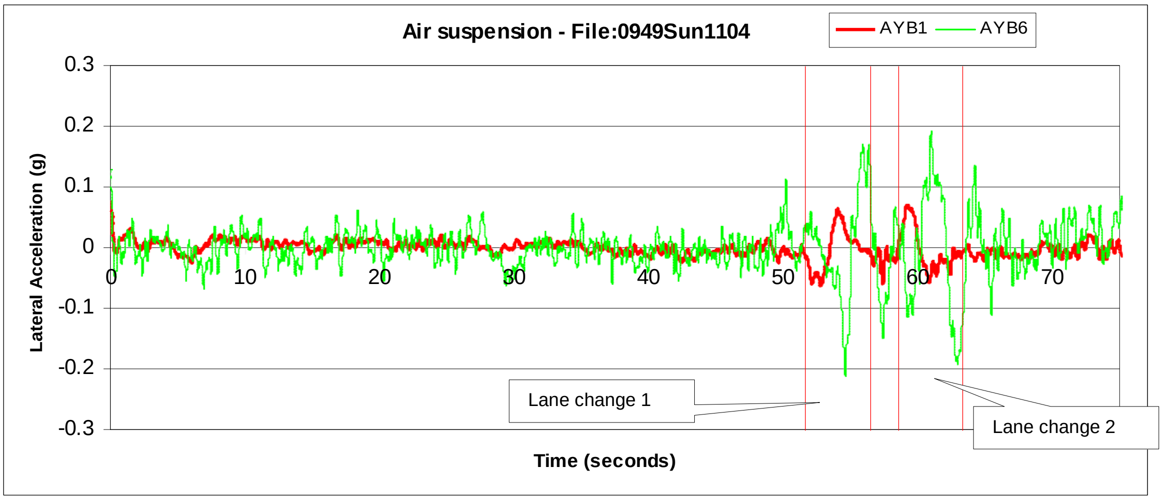
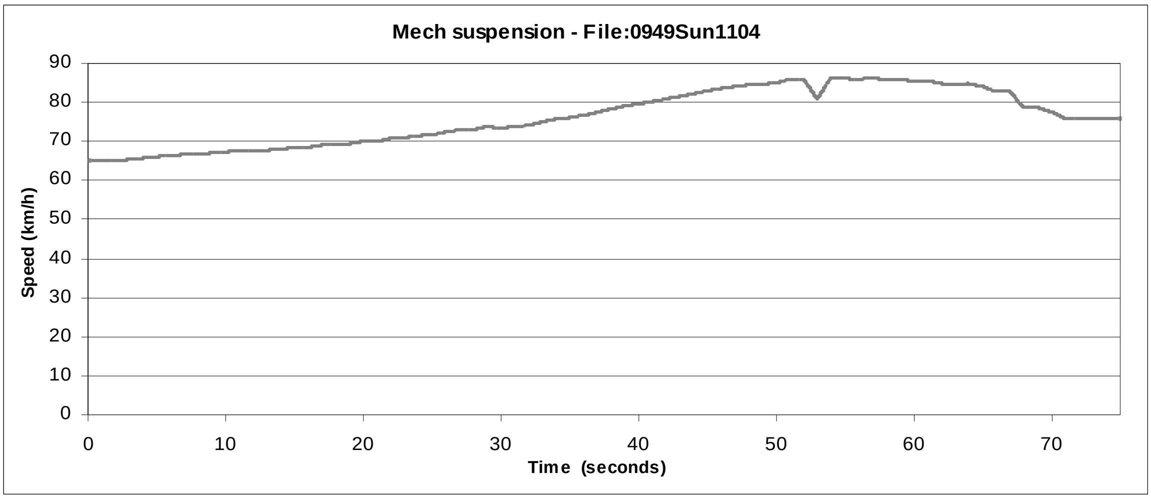


Figure 23. Vehicle 3 Lane change manoeuvre 0949Sun1104

Figure 24 includes three data traces for Vehicle 2 – All air suspension triple roadtrain – File:0949Sun1104. The data traces shown in Figure 24 include data over the 80 second period from beyond the first traffic control point to the completion of the lane change manoeuvre. The top diagram shows lateral acceleration, the middle diagram shows speed and the bottom diagram shows roll angle of the rear trailer.





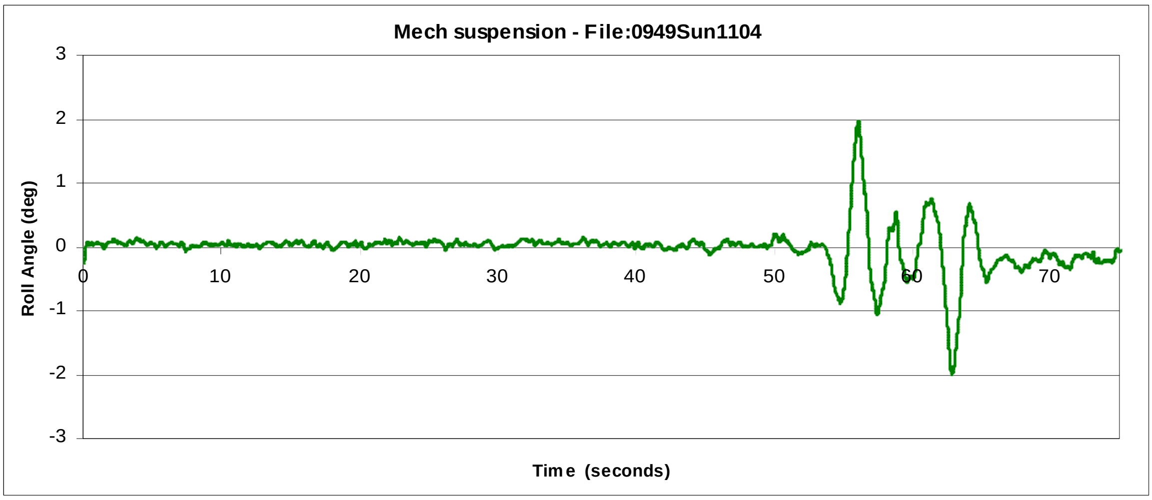


Figure 24. Vehicle 3 Lane change manoeuvre 0949Sun1104

5. TEST RESULTS

5.1 Rearward amplification

Table 8 shows a comparison of the average RA values measured for each vehicle, along with the average speed at which each vehicle's testing was conducted. It is apparent that rearward amplification was similar for all vehicles, with the all mechanical suspension achieving the worst result (highest RA value).

Table 8. All vehicles lane change manoeuvre RA summary

Vehicle No.	1	2	3
Suspension type	Mech dollies /air trailers	All air	All mech
LC A Average	3.2 (81.4 km/h)	3.2 (76.4 km/h)	2.9 (82.7 km/h)
LC B Average	2.2 (80.7 km/h)	2.5 (73.0 km/h)	3.2 (80.8 km/h)
Total Average	2.7 (81.1 km/h)	2.8 (74.7 km/h)	3.1 (81.8 km/h)

5.2 Yaw damping

Yaw damping is defined in PBS [2] as the rate at which 'sway' or yaw oscillations of the rearmost trailer decay after a short duration steer input at the hauling unit. This measure is typically evaluated through vehicle simulation. The simulation process involves a pulse of steering input being applied to a vehicle travelling at a speed of 90 km/h in a straight line. This pulse is a half sine wave that produces a peak angle at the steering road wheel of 3.2° over a time interval of 0.1 seconds.

When carrying out on-road vehicle testing, this pulse input is virtually impossible for the driver to create (although an automated steering controller could be used on a test track). The driver steering inputs that were achievable were measured to be in the range of 0.5 Hz to 2.0 Hz with an amplitude ranging from 0.8 degrees to 2.1 degrees. The resultant vehicle body motions were then measured, giving the yaw damping response. The results of the yaw damping manoeuvres performed for each livestock triple roadtrain combination are shown in Table 7, Table 8 and Table 9. It is apparent that the all-mechanical suspension road train had the best (highest) yaw damping of 14 %, while the all-air suspension road train had the worst yaw damping of 10 %; note that the vehicle speeds for the on-road test circuit were insufficient to determine yaw damping in the manner prescribed in PBS.

Table 9. Air-suspension with mechanical dollies – Yaw damping summary

Vehicle	File	Test	Steer (max) (deg)	Steer (freq) (Hz)	YawB6 (peak1) (deg/sec)	YawB6 (peak2) (deg/sec)	SPEED (km/h)	YDC
1	0703	YD1	0.8	0.7	4.5	1.5	-	14%
1	0703	YD2	0.9	0.6	3.3	1.4	-	13%
1	0703	YD3	0.8	0.9	3.3	1.3	-	15%
1	0703	YD4	0.8	0.8	4.0	2.4	-	8%
1 0703		**Average**	**0.8**	**0.8**	**3.8**	**1.7**	**-**	**13%**

Table 10. All-air-suspension – Yaw damping summary

Vehicle	File	Test	Steer (max) (deg)	Steer (freq) (Hz)	YawB6 (peak1) (deg/sec)	YawB6 (peak2) (deg/sec)	SPEED (km/h)	YDC
2 0731		YD1	1.1	1.7	1.9	1.0	77.0	11%
2 0731		YD2	1.1	1.8	2.0	1.3	74 .0	7%
2 0731		YD3	1.5	2.1	1.9	1.1	74.5	9%
2 0731		YD4	1.4	1.2	2.0	0.8	74.5	14%
2 0731		**Average**	**1.3 1.7**		**2.0**	**1.1**	**75.0**	**10%**

Table 11. All-mechanical-suspension – Yaw damping summary

Vehicle	File	Test	Steer (max) (deg)	Steer (freq) (Hz)	YawB6 (peak1) degs/sec)	YawB6 (peak2)	SPEED (km/h)	YDC
3 0800		YD1	2.1	1.4	4.9	2.8	71.0	9%

3	0800	YD2	2.0	1.6	3.7 1.9 6	.8		10%
3 0800		YD3	1.8	1.8	1.3	-	71.0	-[5]
3	0800	YD4	1.6	1.7	1.8 0.4 7	.0		23%
3 0800		**Average**	**1.9**	**1.6**	**3.5 1.7 7**	**.0**		**14%**

The yaw damping m anoeuvres conducted varied gr eatly between eac h vehicle due to factors such as steering input and s peed. Yaw damping manoeuvres are highly sensitive to speed; if sufficiently high speeds ar e not achievable the vehicle does not exhibit behaviour from whic h yaw damping co-efficients can be accurately estimated. The intial steer ing pulse input tends to vary between vehicles; in addition, it is not possible to utilise a single steering pulse durin g on-road testing, because the st eering pulse c auses the v ehicle to diverge and the driver must continue to steer the vehicl e, creating unwanted ve hicle responses. These additional steering i nputs also vary significantly between manoeuvres . Despite these variations, the averaged Yaw Damping Coefficient (YDC) from these tests do fall wit hin the expected range for eac h of the respective vehicles. However, a more valid comparison between the three test vehicles is given in Table 12.

Table 12 c ontains the yaw damping c o-efficients calculated based on data during and after the completion of the lane change manoeuvres. Using this data provides fair comparison in that the steering input is regulated, as the driver is following markers on the road. The manoeuvre was conducted on the same section of road at maximum achievable speeds . Variations in speed and steering input still exis t but are greatly reduced.

Results from Table 12 show that the al l air suspension vehic le has the worst yaw damping value. The other vehic les demonstrated similar result s, however the all-mechanical suspension vehicle achieves this value at a higher speed. Typically as speed is increased yaw damping worsens, therefore a YDC of 15.5 % at 86.0 km/h is a better result than a YDC of 15.5 % at 82.3 km/h.

Table 12. All vehicles yaw damping summary

Vehicle No.	**1 2 3**		
Suspension	Mech dollies	All air	All mech

[5] YDC not defined due to steering input not able to generate sufficient yawing of rear unit

type /air	trailers		
Speed (max)	82.3 km/h	78.0 km/h	86.0 km/h
LC A	13.4%	11.6%	16.7%
LC B	17.5%	7.7%	14.2%
Average 15.5	**%**	**9.7%**	**15.5%**

5.3 Suspension behaviour

5.3.1 Roll gradient

The roll gradient for each of the test vehicles was calculated based on data collected during lane change manoeuvre tests.

The roll gradients were:

- Vehicle 1 (air/mech) - 7.6 deg/g
- Vehicle 2 (all air) - 7.7 deg/g
- Vehicle 3 (all mech) - 6.9 deg/g

It is apparent that the all mechanical suspension road train had the best (lowest) roll gradient, and the all air suspension road train had the worst (highest) roll gradient. Details of roll gradients of each vehicle are included in Appendix A.

5.3.2 Roll steer coefficient

Roll steer co-efficients were calculated for the rear trailer and rear-most dolly for each of the livestock triple roadtrain combinations. The roll steer co-efficients were calculated based on data collected during lane change manoeuvre tests.

The roll steer coefficients are shown in Table 13. It is apparent that mechanical and air suspensions recorded the same moderate degree of roll steer.

Table 13. Roll steer coefficient

Vehicle Type		Dolly	Trailer
1	Mech dollies /air trailers	N/A 0.08	
2 All	air	N/A	0.08
3 All	mech	0.04	0.08

6. CALIBRATED SIMULATION MODELS

Roaduser has developed a suite of RATED models (Roaduser Autosim Truck Engineering Dynamics) based on UMTRI's Autosim multibody simulation code. Roaduser's Autosim pre-processor allows the user to select an arbitrary vehicle configuration (ie. 6x4 tractor and tandem axle semi-trailer) and generate the entire Autosim Lisp code for the dynamic simulation model. This code is then processed by Autosim to create an error-free, consistent simulation model in executable format.

Vehicle design spreadsheets are used to enter vehicle mass and dimension parameters for the calculation of load distribution between axle groups and other design-related calculations. These spreadsheets are used to automatically generate input parameter files for the Autosim executable model. Common library parameters are stored on Roaduser's fileserver and used consistently in our models unless otherwise specified.

The major performance assessment manoeuvres (SAE lane change, pulse steer input, etc) are automatically simulated for the given vehicle specification using the Autosim executable model. The required simulation parameters (speed, steer path, etc) are obtained by the model from Roaduser's fileserver and applied to the simulation model. This ensures that the simulated manoeuvres are conducted consistently across all simulation projects.

Processing of simulation results is conducted automatically by Roaduser's PBS Analyser, which directly accesses the simulation results files and processes the model output to generate numerical results such as Rearward Amplification and High Speed Transient Offtracking. This ensures that these performance measures are calculated in a consistent fashion at all times.

It is also possible to include variations in road geometry and/or surface roughness in the RATED vehicle models.

In recent years, Roaduser has introduced QA procedures for generating, exercising and referencing simulation models. At the same time, input parameters, particularly suspension and tyre parameters, are continually updated and improved, based on frequent vehicle field testing carried out by Roaduser. New RATED models were developed specifically for the three road trains, reflecting the latest Roaduser modelling developments.

6.1 Model validation and calibration

Before the RATED simulation models were used to evaluate the performance of the combination vehicles, the models were validated against actual test data obtained from the Great Eastern Highway Bypass test site. Any discrepancies between the model behaviour and the test results could be removed by calibration of the models (by adjusting suspension roll stiffness, for example), so that a reliable PBS assessment could then be carried out under standard conditions.

Test conditions which often interfere with the quality of test results include:

- Road cross-fall;

- Driver steering accuracy;
- Vehicle loading; and
- Test speed.

Once the models were validated under the actual (imperfect) test conditions, they could then be used to evaluate the performance of the vehicles under standard conditions (ie. flat road surface with correct driver steer input, axle loads and test speeds).

The models were used to replicate selected test manoeuvres at actual test weights, at the recorded test speeds with the measured road cross-fall applied. Driver steering error during the SAE lane change was replicated also. In all cases very good comparison was observed between the simulation models and the recorded test data, without the need for adjustment of the models in any way.

6.2 Output from calibrated models

Figure 25, Figure 26 and Figure 27 show comparisons of lateral acceleration at the prime mover and the rear trailer for each test vehicle. It can be seen that good comparison between simulation and test was observed without the need for adjustment of the model parameters.

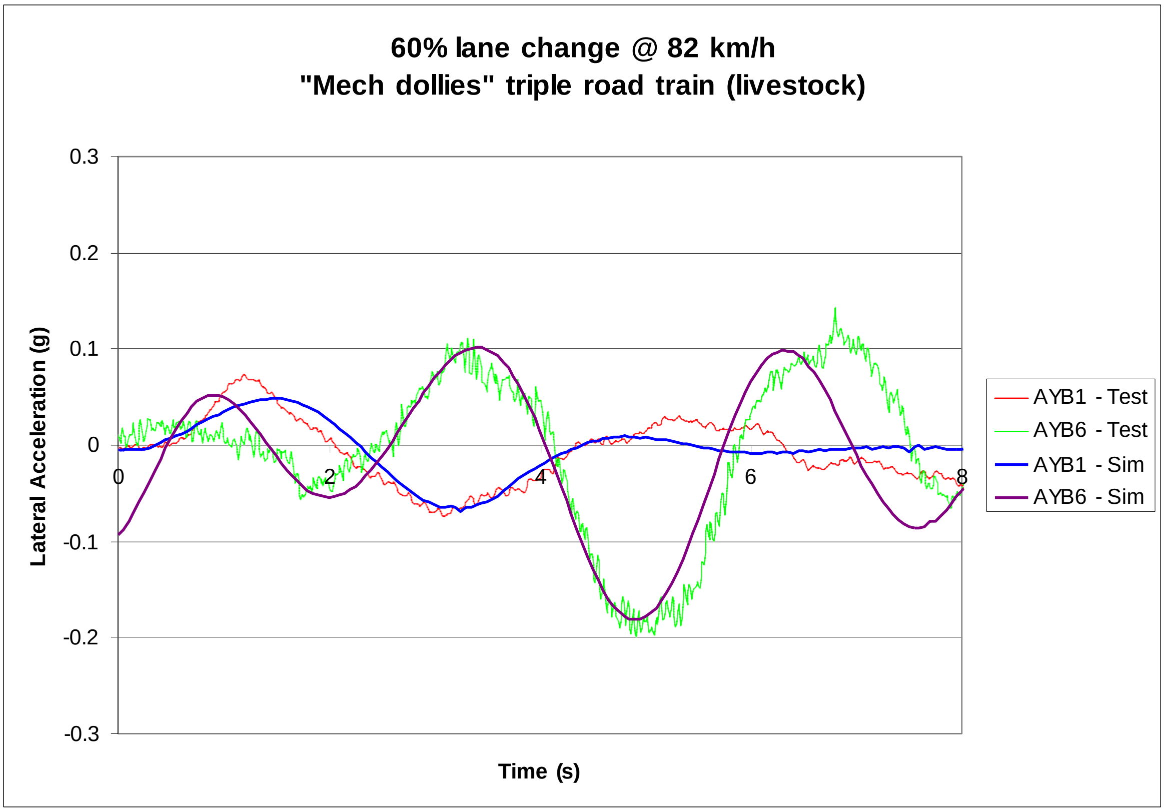


Figure 25. Comparison of test and simulation – Vehicle 1

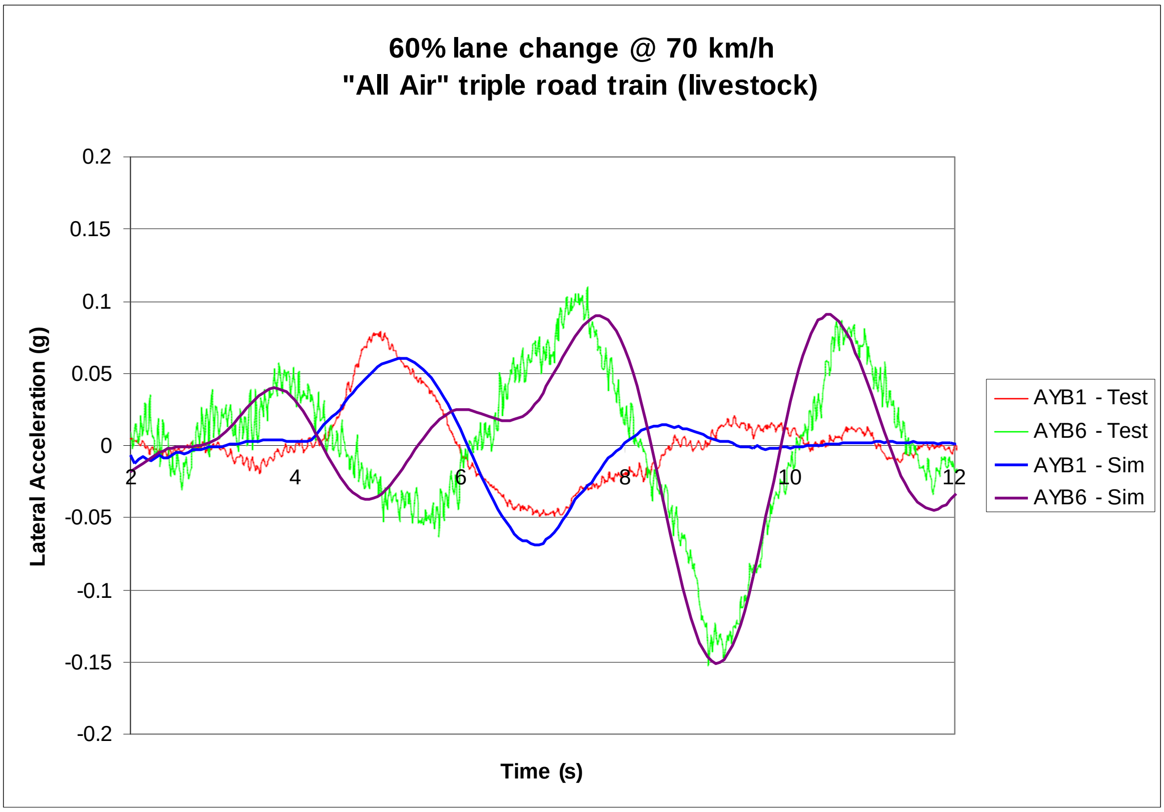


Figure 26. Comparison of test and simulation – Vehicle 2

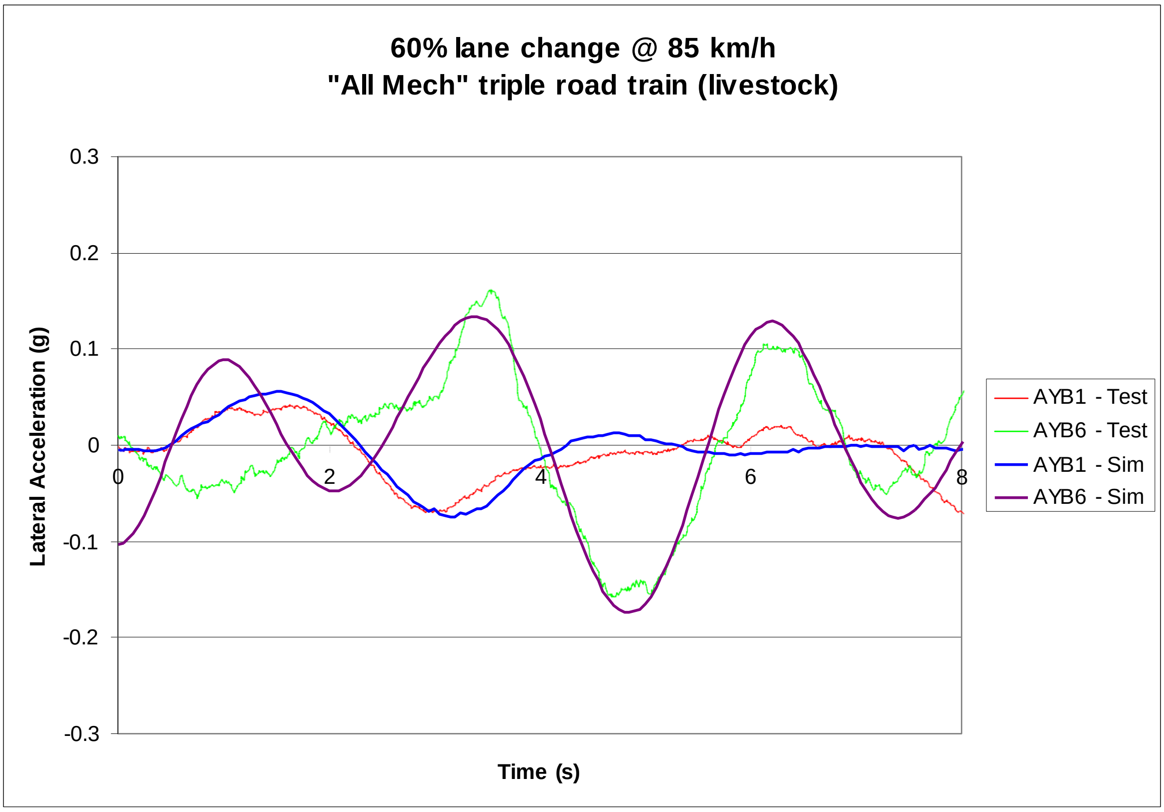


Figure 27. Comparison of test and simulation – Vehicle 3

The models were therefore considered to be validated and sufficient for the purpose of evaluating vehicle performance against PBS standards under standard conditions.

7. PERFORMANCE COMPARISONS USING SIMULATION

7.1 Performance-based standards

Using the models calibrated against the test data, the three combination vehicles were evaluated for the following Performance-Based Standards:

- Tracking Ability on a Straight Path (TASP);
- Static Rollover Threshold (SRT);
- Rearward Amplification (RA);
- High-Speed Transient Offtracking (HSTO); and
- Yaw Damping Coefficient (YDC).

The performance of the vehicles evaluated against Level 4 PBS is summarised in Table 14.

Table 14. Performance of combinations evaluated against Level 4 PBS measures

PBS measure	Performance target (Level 4)	Vehicle 1 (Mech dollies)	Vehicle 2 (All air)	Vehicle 3 (All mech)
TASP	≤ 3.30 m	3.15 m 3 3.18	m 3 3.10	m 3
SRT	≥ 0.35 g	1st unit 0.36 g 3 2nd unit 0.34 g 2 3rd unit 0.34 g 2	1st unit 0.36 g 3 2nd unit 0.33 g 2 3rd unit 0.33 g 2	1st unit 0.36 g 3 2nd unit 0.34 g 2 3rd unit 0.34 g 2
RA	≤ (5.70 × SRTrrcu*)	2.66 2 2.48	2 2.74	2
HSTO	≤ 1.20 m	1.44 m 2 1.48	m 2 1.41	m 2
YDC	≥ 0.15	0.09 2 0.09	2 0.12	2

* rrcu = rearmost roll-coupled unit

Table 14 highlights the differences in performance between the three road trains. Although the differences in SRT are small, the dynamic activity (quantified by the remaining measures) varies more noticeably. Considering that the main differences between the combinations are in the suspensions, these performance variations represent significant effects due to suspension alone.

While the general trend is towards improved performance in the mechanically-suspended combination, the RA results show the opposite trend. RA has a tendency to increase for vehicles with mechanical suspensions, because the improved tracking of the rear trailer produces a more rigid lateral movement than a trailer which takes a wider, more gentle sweep in the lane change (as for an air-suspended trailer). When good HSTO performance is observed, the RA performance can, to some extent, be neglected.

From a PBS point of view, there is definitely an improvement in vehicle performance to be gained by fitting mechanical suspension to the combination.

7.2 Frequency response (lateral acceleration gain) analysis

Lateral acceleration gain was computed for each vehicle using the simulation models in a frequency sweep carried out at a speed of 90 km/h. Figure 28 shows the LA gain plots on the same axes, where the differences in performance between the vehicles can clearly be seen. The two combinations utilising air-suspended trailers exhibit high peaks at around 0.4 Hz, while the mechanically-suspended combination exhibits its highest sensitivity (but lower than the air-suspended combination) in the range 0.4 – 0.6 Hz. This combination is therefore less likely to exhibit unexpected, undesirable behaviour due to driver steering input. There is no distinct “sweet spot” in the LA transfer function of the mechanically-suspended combination that the driver needs to avoid; the driver will notice more consistent behaviour of the combination over the range of steering inputs. The shift to higher frequency also decreases the likelihood of undesirable behaviour, because the general driver steering frequency is at around 0.3 Hz.

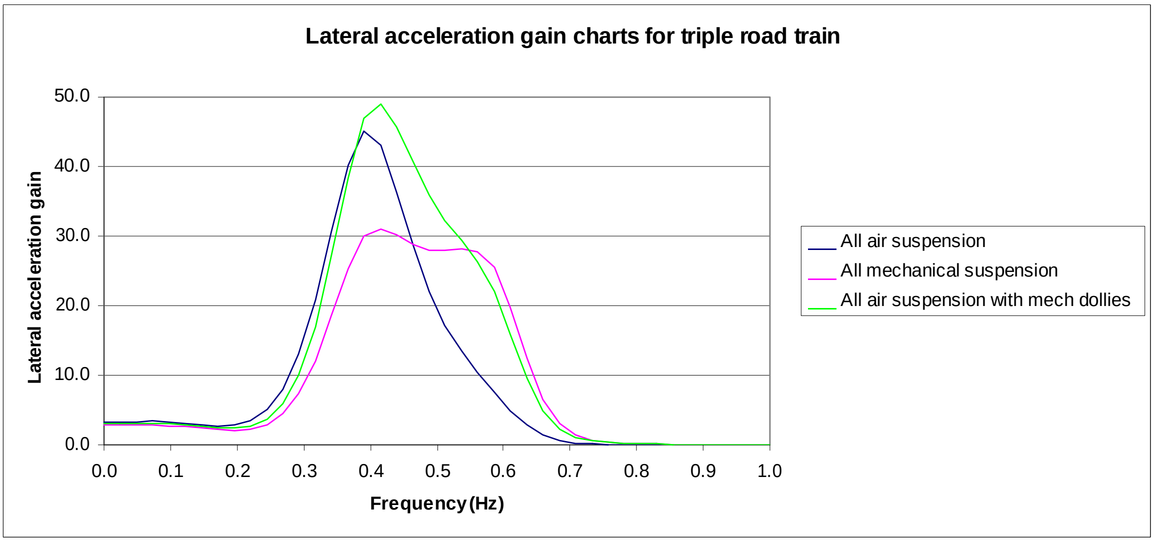


Figure 28. Frequency response comparison, using calibrated models (90 km/h)

7.3 Reliability of simulation models

The RATED simulation models of the three test road trains have proven to be reliable in predicting the key aspects of the measured road train behaviour. Note that this comparison is confined to “open loop” manoeuvres because the driver model used in the simulation models is intended only to provide accurate path following, and cannot represent the full range of complexities of driver behaviour.

With regard to rearward amplification in the lane change manoeuvre, and yaw damping coefficient measurements, Table 15 summarises the predictions of the computer simulation models against the actual test results. As the vehicle speeds varied significantly in the tests, actual vehicle speeds for each test result are noted. It is apparent that:

- Rearward amplification values agree reasonably well; taking into account the speed effect, the simulation slightly under-estimates the rearward amplification; simulation and test agree on the all-mechanical combination having the highest rearward amplification
- Yaw damping coefficient values agree reasonably well, considering that the test speeds were variable and relatively low; simulation and test agree on the all-mechanical combination having the highest yaw damping coefficient.

Table 15. Comparison of simulation and test results (stylised manoeuvres)

Performance measure	Method (Simulation or Test)	Vehicle			Comment
		1 (Air with mech dollies)	2 (All air)	3 (All mech)	
Rearward amplification	**Simulation**	2.66 (88 km/h)	2.48 (88 km/h)	2.74 (88 km/h)	
	Test	2.7 (81 km/h)	2.8 (75 km/h)	3.1 (82 km/h)	Actual speeds below standard speed of 88 km/h
Yaw Damping Coefficient	**Simulation**	9 % (90 km/h)	9 % (90 km/h)	12 % (90 km/h)	
	Test	16 % (82 km/h)	10 % (78 km/h)	16 % (86 km/h)	From lane-change tests – speeds highly variable and below standard speed of 90 km/h

		13 % (-)	10 % (75 km/h)	14 % (70 km/h)	From route tests – speeds well below standard speed of 90 km/h

A further point of comparison is the frequency response (lateral acceleration) of the combination. Comparison of Figure 18 and Figure 28 shows that:

- Simulation and test agree on the all-mechanical combination having a higher and more diffuse dominant frequency, along with significantly lower rearward amplification gain at the dominant frequency
- Simulation and test agree extremely well on the dominant frequency of each combination, and their order of merit (see Table 16).

Table 16. Comparison of simulation and test results (normal driving)

Performance measure	**Method (Simulation or Test)**	**Vehicle**			**Comment**
		1 (Air with mech dollies)	2 (All air)	3 (All mech)	
Dominant frequency of lateral acceleration gain (Hz)	**Simulation**	0.42 0.38		0.42/0.55	
	Test	0.41 0.37		0.5/0.6	Actual speeds below simulation speed of 90 km/h

8. AIR SUSPENSION PERFORMANCE ISSUES

8.1 Air vs mechanical suspension behaviour

Roll gradients were measured for the rear trailer units of each vehicle combination. The mechanical suspension rear trailer unit was found to have a lower roll gradient (and therefore to experience less roll per unit lateral acceleration). By comparison, the all air combination had the highest roll gradient. The measured roll gradients were:

- Vehicle 1 (air/mech) - 7.6 deg/g
- Vehicle 2 (all air) - 7.7 deg/g
- Vehicle 3 (all mech) - 6.9 deg/g

Note that the roll gradients were measured in dynamic manoeuvres, rather than the preferred steady-state manoeuvre. The effect of suspension roll stiffness on trailer roll gradient is likely to reduce for longer vehicle units in dynamic manoeuvres.

The measured *roll steer coefficients* of the air and mechanical suspensions were similar. Simulation shows that suspensions with higher roll steer coefficients exhibit poorer yaw damping and rearward amplification. The all-air suspension vehicle exhibited poor yaw damping qualities but less rearward amplification; this implies that variations in performance between the vehicles are more likely dependent on variations in roll stiffness rather than roll steer.

The increased roll stiffness of the trailer mechanical suspension was found to significantly reduce the roll angle per unit lateral acceleration of the rear trailer in the combination. The increased roll stiffness of the dolly mechanical suspension, when incorporated with air-suspended trailers, also reduced the roll angle per unit lateral acceleration of the rear trailer of the combination.

8.2 Yaw/roll dynamics

Rearward amplification was similar for all vehicles, with the all mechanical suspension achieving the worst result (highest RA value). The mechanical suspension (with greater roll stiffness) consequently experiences less roll, which causes the vehicle to maintain a tighter line during high speed testing manoeuvres, resulting in better HSTO and YDC values. As the vehicle combination is “stiffer” and follows a tighter line, the lateral accelerations of the rear units of the combination are increased. This is the cause of a higher rearward amplification value.

However, the *lateral acceleration gain*, which covers a range of frequencies rather than the essentially single frequency (0.4 Hz) of the lane change manoeuvre, was found to vary dramatically as a function of suspension. Air suspension caused the triple road train livestock combination to adopt a low dominant frequency of combined yaw and roll behaviour (0.37 – 0.38 Hz). Mechanical suspension caused this dominant frequency to increase significantly and to separate into two dominant frequencies of lesser gain (occurring in the range 0.42 – 0.6 Hz); these frequencies appear to represent predominantly yaw behaviour and predominantly roll behaviour respectively. It appears that air suspension, with its lower roll stiffness, causes the yaw and roll modes to merge into a high gain, single dominant mode at a relatively low frequency.

The use of a mechanical dolly with the air-suspended trailers did not greatly affect rearward amplification (PBS measure) but brought about some improvement in the lateral acceleration gain responses: the dominant frequency increased by approximately 10 % and the overall response profile moved significantly towards the higher frequencies.

Yaw damping was found to be relatively poor for the air-suspended triple road train livestock combination and the test results found that this improved significantly for the all-mechanical combination and for the air trailers with mechanical dollies. While the simulation predicted this improvement for the all-mechanical combination it did not predict an improvement for the mechanical dollies with the air-suspended trailers. In relation to comparing simulation and test, the yaw damping test results are problematic in that:

- It is not possible to generate the prescribed PBS steering pulse using a human driver
- Test speeds were in many cases well below the 90 km/h (or maximum vehicle speed) prescribed in PBS.

High speed transient offtracking (HSTO) was not directly tested. However, simulation results showed that the all air suspension achieved the worst results (greatest HSTO), with all mechanical suspension performing best. The combination with air suspended trailers and mechanical dollies produced a result between the two.

The computer-based predictions made in the Stage 1 report (relevant to livestock triple road trains) have been reviewed against the findings from the tests, with the following outcome:

- The dominant yaw/roll frequency of the livestock triple was predicted to be in the range 0.3 – 0.4 Hz; this was found to be so for the air-suspended test vehicles, while the dominant frequency of the mechanically-suspended test vehicle was significantly higher
- It was predicted that generic mechanical suspension would increase the dominant yaw/roll frequency by 0.1 Hz, or 20 %; this was found to be approximately correct, although the tests showed a somewhat stronger effect, with the dominant frequency increasing by 0.1 – 0.2 Hz, or 25 – 50 %
- It was predicted that yaw damping of livestock triples would be below the (then) PBS value of 15 %; this was found to be so, considering that the actual test speeds were significantly lower than 90 km/h and yaw damping is known to decrease with speed
- It was predicted that generic air suspension would produce less than half the damping of the generic mechanical suspension; this appears to have been an exaggeration, with the tested air suspension reducing yaw

damping by approximately 25 % relative to the tested mechanical suspension

- Roll stiffness was predicted to be the most influential suspension parameter, and this has been confirmed.

Based on the above review, the Stage 1 computer-based predictions of yaw/roll dynamics issues influenced by suspension parameters have proven to be remarkably accurate and useful.

8.3 Driver-vehicle behaviour

The driver's steering input provides a measure of the controllability of the vehicle combination. *Steering amplitude* (RMS steering angle) was approximately 20 % less for the all-mechanical and mechanical dolly vehicles. While this may reflect variations in prime mover steering sensitivity (which would be related to prime mover wheelbase), the same prime mover was used in Vehicles 1 & 2. It is likely therefore, but not definitive, that the all air combination required more steering effort on the part of the driver.

This is confirmed by the vehicle motion variables. Prime mover *lateral acceleration* (RMS value) was found to be 29 % less for the all-mechanical combination and 21 % less for the mechanical dolly combination. These improvements were amplified at the rear trailer, where the lateral acceleration (RMS value) was 47 % less for the all-mechanical combination and 44 % less for the mechanical dolly combination. This was also confirmed in the *yaw rate* (RMS value) of the rear unit (62 % less for the all-mechanical combination and 21 % less for the mechanical dolly combination) and in the *roll angle* (RMS value) of the rear unit (72 % less for the all-mechanical combination and 25 % less for the mechanical dolly combination).

Further insight into the effect of suspension on the ability of the driver to control the vehicle combination was provided by the *power spectrum of the steering angle* and its relationship to the *frequency sweep of lateral acceleration gain* from the prime mover to the rear unit. It was found that the dominant steering frequencies were all below 0.4 Hz, and the driver of the mechanically suspended combination had the lowest frequency (0.27 Hz); low steering frequencies are generally associated with more relaxed and less demanding driving situations. In contrast, the dominant vehicle response frequency was highest for the mechanically suspended combination (0.5 – 0.6 Hz) and was lowest for the air suspended combination (0.37 Hz); in order to ease the driver's steering control task, the dominant vehicle response frequency should not coincide with the driver's steering frequency.

The clear separation between the driver's steering input and the combination vehicle's response, in the case of the mechanical suspension, is illustrated in Figure 29. In contrast Figure 30 shows the situation for the air-suspended combination. In this case, the driver steers at a somewhat higher frequency (because the task is more difficult) and the vehicle responds at a much lower frequency, causing the two frequencies to coincide. This means that the bulk of the driver's steering corrections cause an exaggerated response at the rear unit, and the driver is unable to avoid this occurring. Figure 31 shows the same comparison for the vehicle combination with mechanical dollies; while the two frequencies are still reasonably close together, there is a degree of separation and the exaggerated vehicle response will be less apparent to the driver.

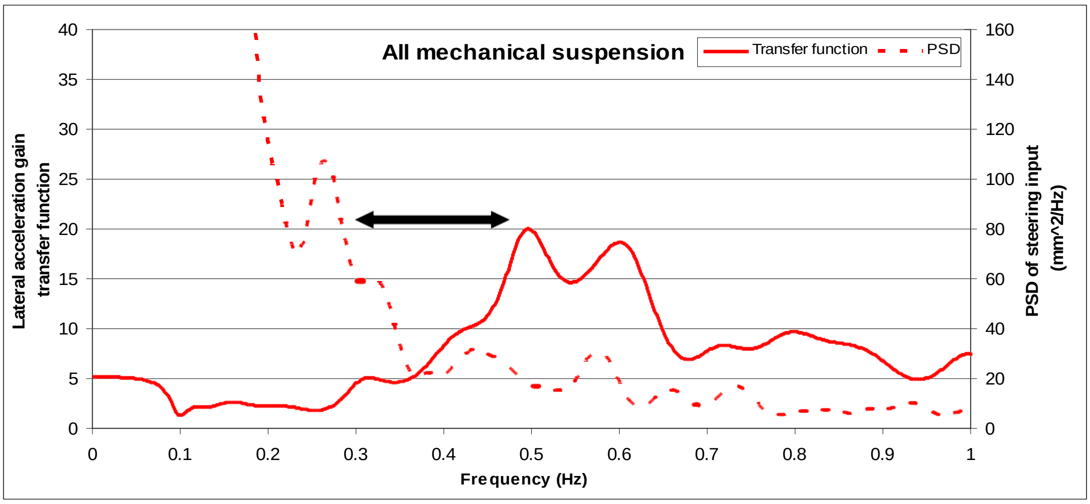


Figure 29. Spectral analysis of driver input and vehicle response

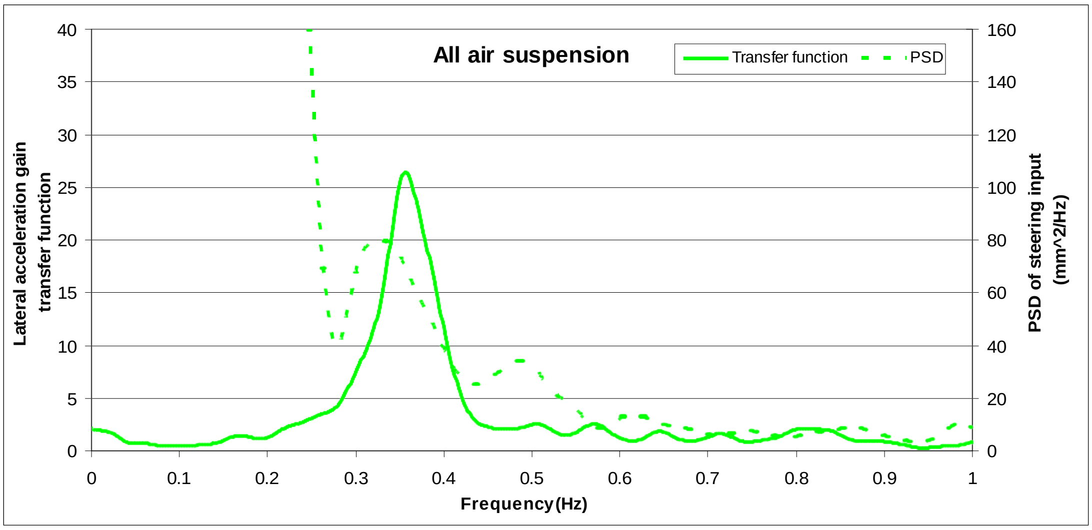


Figure 30. Spectral analysis of driver input and vehicle response

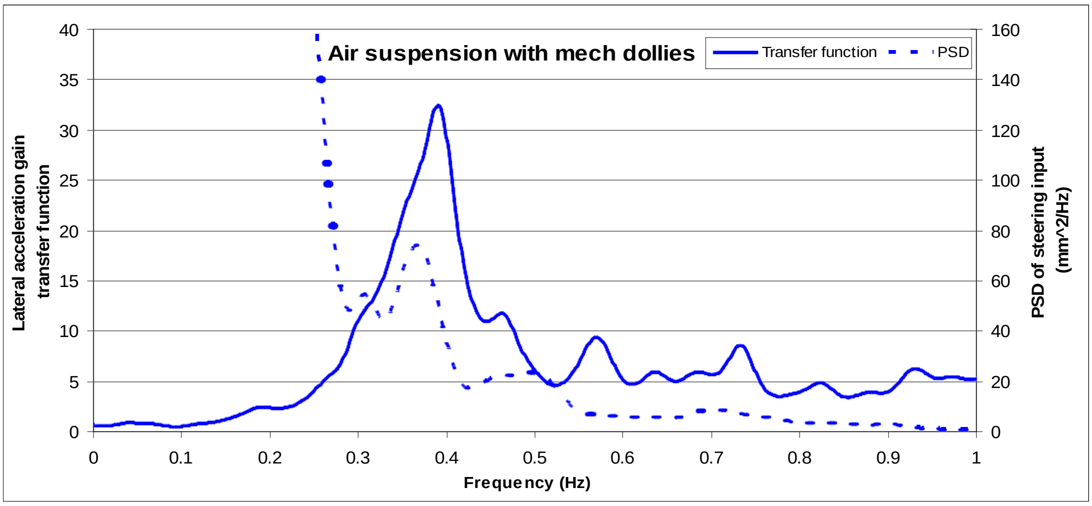


Figure 31. Spectral analysis of driver input and vehicle response

The ultimate test of the quality of the driver-vehicle controllability, as illustrated in Figure 29, Figure 30 and Figure 31, is the amount of lateral movement, yawing, rolling or swaying at the rear unit. Table 17 summarises the relevant test results and confirms that:

- Lateral acceleration of the rear unit was virtually halved with either all mechanical of mechanical dolly combinations
- Yaw rate of the rear unit was reduced by 62 % for the all mechnical combination and by 23 % for the mechanical dolly combination
- Roll angle of the rear unit was reduced by 72 % for the all mechnical combination and by 25 % for the mechanical dolly combination.

It may be concluded that, relative to the all-air combination, there was a dramatic improvement in driver-vehicle controllability with all mechanical suspension. There was also a significant and worthwhile improvement with the use of mechanical dollies with air-suspended trailers.

Table 17. Lateral movement of rear unit by vehicle/suspension type

Performance measure	**Vehicle**		
	1 (Air with mech dollies)	2 (All air)	3 (All mech)
RMS lateral acceleration (g)	0.024 (56 %)	0.043 (100 %)	0.023 (53 %)
RMS yaw rate (deg/sec)	1.030 (77 %)	1.310 (100 %)	0.500 (38 %)
RMS roll angle	0.110 0.146		0.041

(deg)	(75 %)	(100 %)	(28 %)

Note that the Stage 1 report predicted the suspension-related yaw/roll dynamic issues confirmed above in Section 8.2 but was not able to address the driver behaviour issues. The testing has confirmed not only that the suspension-related yaw/roll dynamic issues exist, but also that they dramatically affect the ability of the driver to control the vehicle combination.

8.4 Rollover limits

Rollover limits are similar for all vehicles, with the all-air-suspension vehicle having a worse SRT value (ie. lower) than the all mechanical and mechanical/air combination. The lowest SRT value for the all-air-suspension vehicle was 0.33 g, whereas the lowest SRT value for the all mechanical and the mechanical/air combination was 0.34 g; both of these values are below the PBS standard of 0.35 g minimum.

8.5 Prime mover handling

Prime mover handling was not investigated due to instrumentation constraints. The potential issue raised in the Stage 1 report related only to the prime mover suspension. The matter of prime mover handling is not affected by the trailer and dolly suspensions.

9. CONCLUSIONS

(1) The predictions of road train livestock triple combination behavioural issues determined from the Stage 1 report computer simulations were essentially confirmed in the test program, namely:

a. The yaw/roll response of the combination to driver steering input is exaggerated at a relatively low dominant frequency

b. The tests confirmed that the dominant frequency is increased very significantly when mechanical suspensions are used. This increase was found to have a positive effect on drivers as it made their task to control the vehicle easier and consequently less tiring; a worthwhile increase in this dominant frequency also occured when mechanical suspension dollies were used with the air-suspended trailers

c. This change in dominant frequency is primarily related to suspension roll stiffness: the mechanical suspension tested was stiffer and increased the dominant frequency

d. When the dominant yaw/roll response frequency is sufficiently higher than the driver's predominant steering frequency, exaggerated responses (swaying, yawing and rolling) of the rear unit are reduced and driver control is dramatically improved; this was achieved with the mechanical suspension tested on trailers and dollies; when the dollies only had mechanical suspension, there was also a worthwhile improvement in controllability of the combination.

(2) Further means of quantifying the performance of the combination vehicles with alternative suspension arrangements were also examined:

a. The yaw damping (a PBS vehicle measure) was relatively poor for the livestock triple combinations and the air-suspended test combination had the worst yaw damping

b. Yaw damping of all combinations tested was generally below current PBS recommendations; however, yaw damping is difficult to measure accurately in practice during on-road tests

c. The rearward amplification (a PBS vehicle measure) was slightly worse for the mechanically-suspended test combination; this measure was not particularly helpful in identifying steering control issues for the triple road trains

d. Two further PBS vehicle measures, Tracking Ability on a Straight Path (TASP) and High-Speed Transient Offtracking (HSTO) were examined using calibrated simulation models and confirmed that the air-suspended combination had worse performance than the mechanically-suspended combination; these measures also confirmed that the mechanical dollies had intermediate performance; the relatively small changes in these measures between vehicles/suspensions were not truly indicative of the driver-vehicle control differences which were measured during the tests.

e. The same roll steer coefficients were measured for all test vehicles; this implies that roll stiffness alone is a significant contributor to controllability of the vehicle combination; further investigation of roll steer coefficients is warranted.

f. The load distribution within axle groups of the test vehicles was generally satisfactory, was superior for the air suspensions, and it is considered that this did not affect the test results.

10. RECOMMENDATIONS

(1) Guidelines for suspensions used on heavy, high centre of gravity multi-combinations such as triple road trains carrying livestock should be developed, taking into account:

a. The ability of mechanical suspension on trailers and dollies (as tested) to dramatically increase the controllability of such vehicle combinations

b. The ability of mechanically-suspended dollies to make a worthwhile contribution to the controllability of such combinations with air-suspended trailers

c. The contribution of air suspension to reducing road wear and to improving ride quality for the livestock; this should include consideration of the additional trailer sway and roll with air suspension and consequent effects on dynamic wheel loading and ride quality

(2) The development of guidelines for suspension use on triple road trains including those carrying livestock should be supported by:

a. Reasonable means of suspension classification which are acceptable to suspension manufacturers

b. Clear guidelines for suspension use based on safety performance of the triple combination

c. Practical means of defining triple livestock combinations which are subject to the suspension recommendations

d. Consideration of the mass to be permitted on subject trailers when used in combinations other than triple road trains

e. Monitoring of the effectiveness of the guidelines, initially with operator surveys and with testing as required.

11. REFERENCES

[1] Operational Stability and Performance of Air Suspensions on various Vehicle Configurations – Estill and Associates Pty Ltd – September 2000

[2] PBS Safet y Standar ds for Heavy Vehicles - National Road Transport Commission – January 2003

[3] Stability and On-Road Performance of Multi-Combination Vehicles with Air Suspension Systems -Stage 1 Project – Roadus er S ystems Pty Ltd – June 2002.

APPENDIX A Alternative vehicle configurations

Further to the analysis of triple road train livestock configurations presented in the main body of this report, similar testing and computer simulation has been carried out for the following innovative vehicle configurations:

- BAB-quad livestock road train with air suspension (except for mechanical dolly);
- A+A+B side tipper combination with air suspension, laden to: (i) standard national axle mass limits and (ii) concessional mass limits (as are available in WA); and
- A+B3 container combination with mechanical suspension, nominally laden to standard national axle mass limits.

The analysis of these additional vehicles has been documented in this appendix for the purpose of demonstrating

(i) the improvements in dynamic performance that can be achieved through the use of innovative vehicle configurations;

(ii) the potential suitability of air suspension systems for certain innovative vehicle configurations; and

(iii) the ability to predict the dynamic performance of innovative vehicle configurations with reasonable accuracy using computer simulation (and that accurate simulation modelling is not limited only to conventional triple bottom road trains).

Dimensioned drawings of these vehicles are shown in Figure 32, Figure 33 and Figure 34.

Photographs of the BAB-quad, A+A+B and A+B3 combinations are shown in Figure 35, Figure 36 and Figure 37 respectively.

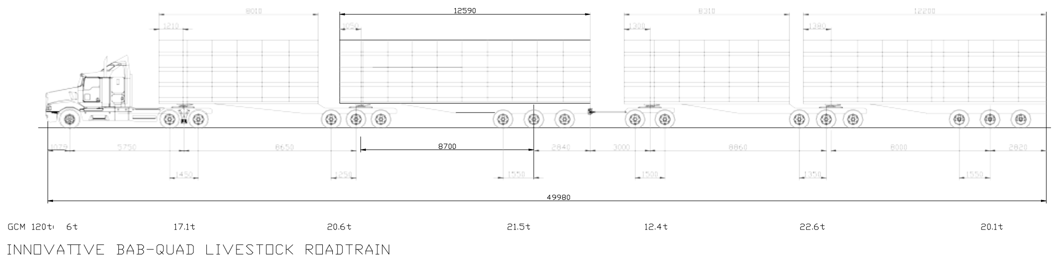


Figure 32. Innovative BAB-quad

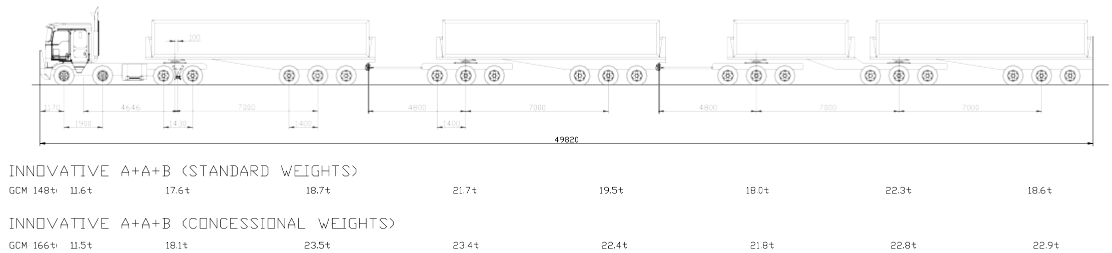


Figure 33. Innovative A+A+B

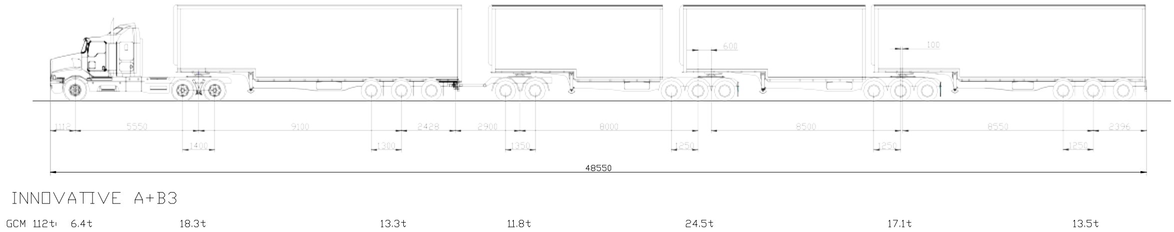


Figure 34. Innovative A+B3[6]

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[6] Diagram shows trailers as curtainsiders, although one curtainsider and three skel trailers were supplied for testing.

Figure 35. BAB-quad livestock combination

Figure 36. A+A+B side-tipper combination

Figure 37. A+B3 container combination

Loading and axle weights

Loading and axle weight summaries of the BAB-quad, A+A+B and A+B3 combinations are shown in Table 18, Table 19 and Table 20 respectively.

Table 18. Test weight summary – BAB-quad combination

Vehicle	**Axle group load (t)**							**GCM (t)**
	Steer	**Drive**	**T1**	**T2**	**Dolly**	**T3**	**T4**	
BAB-quad	6.0	17.1	20.6	21.5	12.4	22.6	20.1	**120.3**

Table 19. Test weight summary – A+A+B combination

Vehicle	**Axle group load (t)**								**GCM (t)**
	Steer	**Drive**	**T1**	**Dolly**	**T2**	**Dolly**	**T3**	**T4**	
A+A+B *(standard weights)*	11.6	17.6	18.7	21.7	19.5	18.0	22.3	18.6	**148.0**
A+A+B *(CSL weights)*	11.5	18.1	23.5	23.4	22.4	21.8	22.8	22.9	**166.4**

Table 20. Test weight summary – A+B3 combination

Vehicle	**Axle group load (t)**							**GCM (t)**
	Steer	**Drive**	**T1**	**Dolly**	**T2**	**T3**	**T4**	
A+B3 *(standard weights)*	6.4	18.3	13.3	11.8	24.5	17.1	13.5	**111.9**

Table 21 is a summary of the RMS values logged during the lead up time for a lane change manoeuvre. Comparing the RMS values obtained for these innovative vehicles with those obtained for the triple road train livestock vehicles in Table 4, it can be seen that the innovative vehicles exhibit far less movement at the rear trailer. The innovative vehicles exhibited less roll and yaw of the rearmost trailers than the triple road trains.

Even though the steer input was similar for all innovative vehicles, the BAB quad had consistently worse RMS results for body roll and lateral acceleration than the other three innovative vehicles. This was attributed to the higher COG height of the vehicle.

Table 21. RMS values during lane change lead up

Vehicle	BAB-quad (Stock)	A+A+B (Tipper)	A+A+B CLS (Tipper)	A+B3 (Container)
File	1719 1007 1117 1651			
Speed (max)	73.0 km/h	82.2 km/h	78.3 km/h	78.0 km/h
RMS Steer (deg)	0.168	0.166 0.187 0.257		
RMS Yaw-rate rearmost trailer (deg/s)	0.256 0.616 0.752 0.557			
RMS Roll angle Rearmost trailer (deg)	0.089 0.035 0.033 -			[7]
RMS Lateral Acc. Prime mover (g)	0.006 0.008 0.011 0.015			
RMS Lateral Acc. Rearmost trailer (g)	0.043 0.014 0.017 0.012			

[7] Vehicle was not instrumented to measure roll angle

Figure 38 shows a sample lane change data trace for the BAB-quad combination. AYB1 represents lateral acceleration of the prime mover, AYB5 represents lateral acceleration of the second last trailer and AYB6 represents lateral acceleration of the last trailer. AYB5+AYB6 is the instantaneous average of the last two trailers, which is used to take account of the roll-coupling between the two trailers.

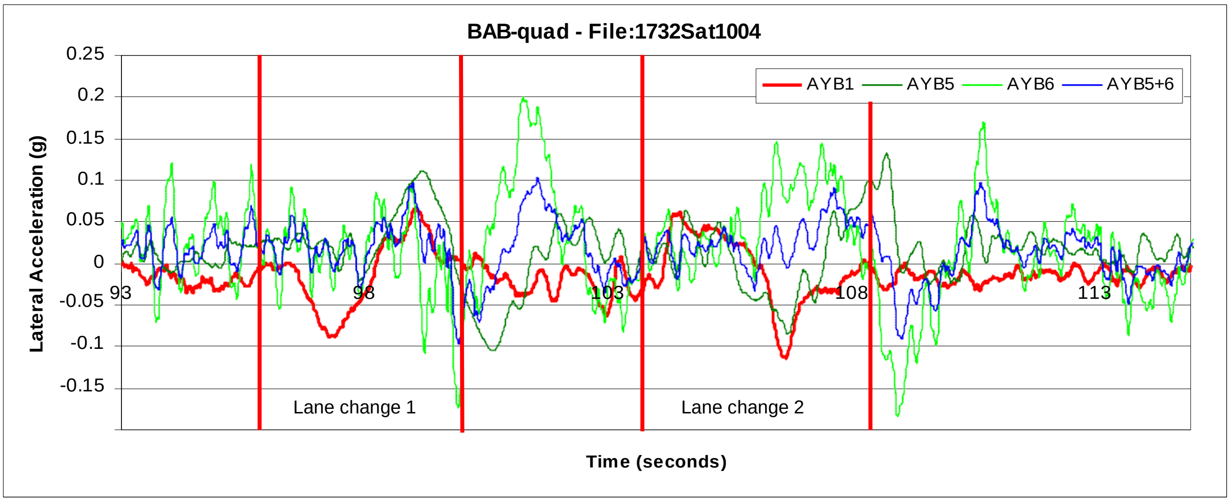

Figure 38. Sample lane change manoeuvre for BAB-quad

Table 22 is a summary of the BAB-quad performing consecutive lane change manoeuvres. It can be seen that the rearward amplification is excellent (in some cases less than 1.0) and yaw damping as measured on the exit of the manoeuvre is on average around 13-14%.

Table 22. BAB-quad lane change manoeuvre summary

File Test		AYB1 (max) (g)	AYB5+6 (max) (g)	V (km/h)	RA	YDC
1719Sat1004	LC 1A (60%)	0.0688	0.0781	72.6	1.1	12.3 %
1719Sat1004	LC 1B (60%)	0.1035	0.0760	69.5	0.7	8.7 %
1732Sat1004	LC 2A (60%)	0.0673	0.1048	76.7	1.6	24.3 %
1732Sat1004	LC 2B (60%)	0.1123	0.0885	71.5	0.8	14.3 %
1744Sat1004	LC 3A (60%)	0.0690	0.1154	81.9	1.7	14.7 %

1744Sat1004	LC 3B (60%)	0.0799	0.1271	80.5	1.6	12.2 %

Figure 39 shows a sample lange change data trace for the A+A+B combination. The last two trailers have again been averaged to take account of roll-coupling.

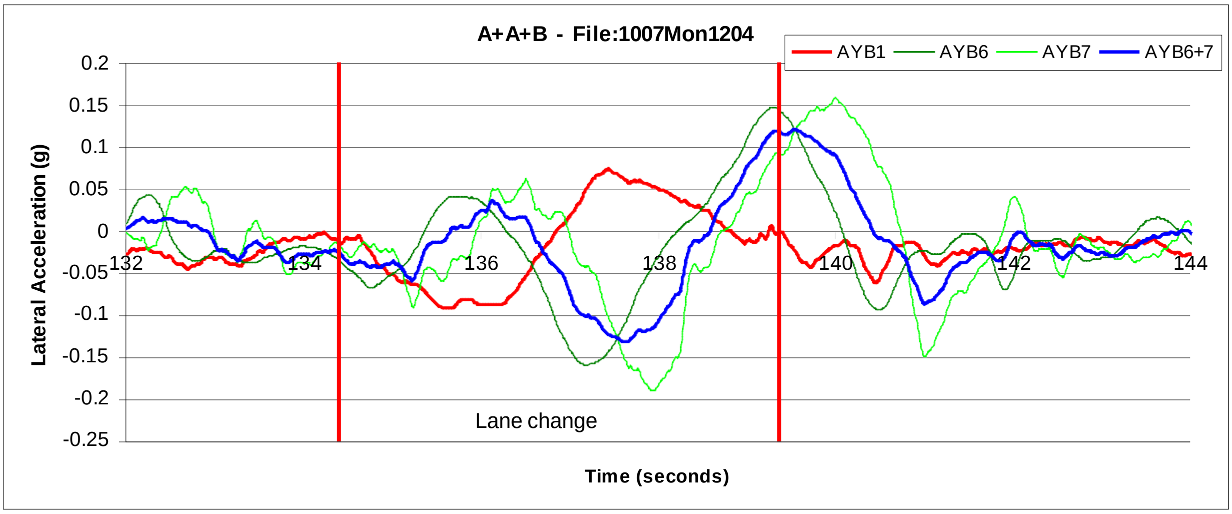

Figure 39. Sample lane change for A+A+B

Table 23 is a summary of the A+A+B lane change manoeuvres. It can be seen that the rearward amplification results are well below those from the triple road train results. This is due to the increased stability of the roll coupling between bodies and the lower COG height.

Table 23. A+A+B lane change manoeuvre summary

Vehicle	File	Test	AYB1 (max) (g)	AYB6+7 (max) (g)	Roll (max) (deg)	V (km/h)	RA	YDC
A+A+B	0942Mon1204	LC 1 (60%)	.0574	.0894	0.26	79.5	1.6	11.6%
A+A+B	0954Mon1204	LC 2 (100%)	.068	.0985	0.29	78.5	1.5	7.2%
A+A+B	1007Mon1204	LC 3 (100%)	.0898	.131	0.30	82.2	1.5	5.8%

Figure 40 shows a sample lane change data trace for the A+A+B combination at CLS weights.

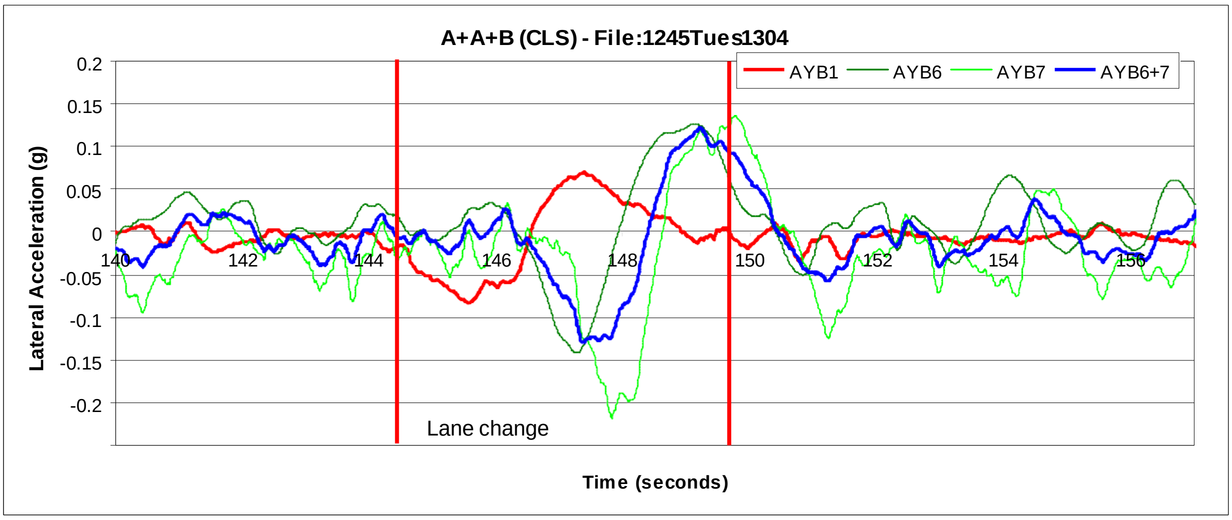

Figure 40. Lane change for A+A+B CLS – 1245 Full width

Table 24 is a summary of the lane change manoeuvres performed by the A+A+B (CLS) combination. With the extra weight on this vehicle the RA is increased by, on average, 13% over that of the same vehicle loaded to general mass limits. It can also be seen that both the lateral acceleration and roll angle is increased.

Table 24. A+A+B CLS lane change manoeuvre summary

Vehicle	File	Test	AYB1 (max)	AYB6+7 (max)	Roll (max)	V (km/h)	RA	YDC
A+A+B	1105 Tue1304	LC 1 (100%)	0.0605	.0995	.384	76.1	1.64	12.6%
A+A+B	1117Tue1304	LC 2 (100%)	0.0521	.1058	.360	78.3	2.03	14.3%
A+A+B	1135Tue1304	LC 3 (100%)	0.0624	.1119	.395	78.6	1.79	9.8%
A+A+B	1245Tue1304	LC 4 (100%)	0.0697	.1226	.413	76.8	1.76	9.6%

Figure 41 shows a sample lane change data trace for the A+B3 combination. In this case, the last three trailers are roll-coupled. Therefore, the last three lateral acceleration signals are instantaneously averaged.

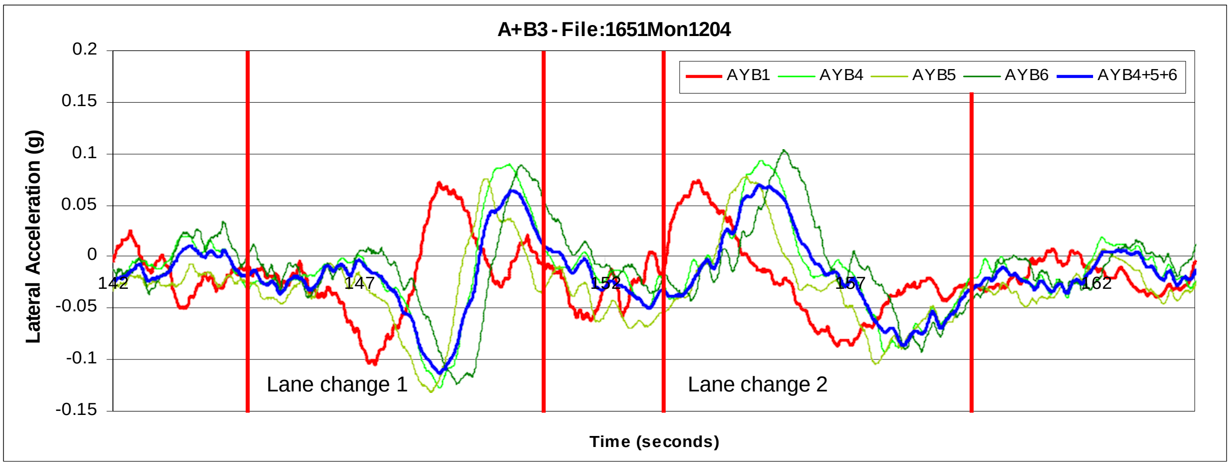

Figure 41. Lane change for A+B3 – 1651 Reduced 60% width

Table 25 is a summary of the lane change manoeuvres performed by the A+B3 combination. The A+B3 had excellent dynamic performance. Notice that the RA and the average lateral accelerations experienced by the rearmost roll coupled units are superior to all other innovative vehicles tested.

Table 25. A+B3 Lane change manoeuvre summary

Vehicle	File	Test	AYB1 (max)	AYB4+5+6 (max)	V (km/h)	RA	YDC
A+B3	1651Mon1204	LC 1A (60%)	.0727	.0645	78.0	.89	-
A+B3	1651Mon1204	LC 1B (60%)	.0746	.0703	78.0	.94	34.0%
A+B3	1621Mon1204	LC 2A (60%)	.0662	.0508	79.8	.77	-
A+B3	1621Mon1204	LC 2B (60%)	.0715	.0554	77.9	.78	10.9 %
A+B3	1609Mon1204	LC 3 (60%)	.0857	.0842	76.4	.98	-
A+B3	1609Mon1204	LC 3 (60%)	.0513	.0458	73.4	.89	38.5%

Table 26 is a summary of the average yaw damping coefficients based on yaw motion experienced after a lane change manoeuvre. Table 26 contains all test results for yaw damping performed during lane change manoeuvres. It can be seen that the A+B3 demonstrated the best overall yaw damping performance, while the two A+A+B combinations demonstrated the worst performance.

Table 26. Yaw damping summary

Vehicle	**BAB-quad (Stock)**	**A+A+B (STD) (Tipper)**	**A+A+B (CLS) (Tipper)**	**A+B3 (Container)**
Speed (max)	75.5 km/h	80.1 km/h	77.5 km/h	76.4 km/h
Average YDC	**19.3 %**	**8.2 %**	**11.6 %**	**27.8 %**

During the open road testing the driver was instructed to provide a pulse steering input to the vehicle rather than following markers on the road. Variation exists between the steering inputs. The steer angle maximum value and frequency are included in the table as a means of comparing these differences in steering input. The speed at which the manoeuvres could be performed also varied depending on the mass of the vehicle and traffic conditions. It is evident that the average speeds achieved by the A+A+B (standard weights) and the A+B3 were significantly higher than the A+A+B (CLS weights).

Table 27 contains the results of the yaw damping manoeuvres performed during open road testing of the BAB-quad innovative combination.

Table 27. BAB-quad File:1747

Vehicle	**Event**	**Test**	**Steer (max) (deg)**	**Steer (freq) (Hz)**	**YawB6 (peak1) (deg/sec)**	**YawB6 (peak2) (deg/sec)**	**SPEED (km/h)**	**YDC**
BAB	1287	YD1	1.1	1.5	1.70	0.41	71.6	22.2 %
BAB	1301	YD2	1.5	1.4	1.58	0.50	69.3	18.0 %
BAB	1326	YD3	1.1	1.7	1.41	0.59	69.8	13.8 %
	Average		**1.2**	**1.5**	**1.56**	**0.50**	**70.2**	**18.0 %**

Table 28 contains the results of the yaw damping manoeuvres performed during open road testing of the A+A+B at standard weights.

Table 28. A+A+B (standard weights) File:0705

Vehicle	Event	Test	Steer (max) (deg)	Steer (freq) (Hz)	YawB6 (peak1) (deg/sec)	YawB6 (peak2) (deg/sec)	SPEED (km/h)	YDC
A+A+B	1239	YD1	1.6	1.4	3.88	1.92	67.5	11.1%
A+A+B	1248	YD2	1.5	1.3	3.79	0.80	67.4	24.0%
A+A+B	1256	YD3	1.7	1.3	2.79	0.31	66.5	33.2%
A+A+B	1267	YD4	0.5	1.7	5.13	1.83	67.1	16.2%
A+A+B	1479	YD5	1.4	0.9	5.21	2.06	74.2	14.6%
A+A+B	1490	YD6	0.9	1.0	4.47	1.43	69.5	17.8%
	Average		**1.3**	**1.3**	**4.21**	**1.39**	**68.7**	**19.5%**

There is considerable variation in the YDC values obtained during the open road testing due to the variations in driver steering input, specific locations at which the manoeuvres were carried out, and test speeds.

Table 29 contains the results of the yaw damping manoeuvres performed during open road testing of the A+A+B at CLS weights. Due to the increased mass of the A+A+B combination at concessional weights it can be seen that the average yaw damping coefficient is lower than that of the same vehicle running at standard higher mass limits.

Table 29. A+A+B (CLS weights) File1:0623 File2:0709

Vehicle	Event	Test	Steer (max)	Steer (freq)	YawB6 (peak1)	YawB6 (peak2)	SPEED (km/h)	YDC
A+A+B 1-	683	YD1	2.3	1.4	2.99	0.71	56.5	22.4%
A+A+B 1-	695	YD2	1.9	1.6	3.50	1.18	61.0	17.1%
A+A+B 1-	1490	YD3	1.2	1.5	1.59	0.84	58.1	10.2%
A+A+B 1-	1512	YD4	1.7	1.6	3.41	0.88	60.4	21.1%
A+A+B 2-	660	YD5	2.4	1.3	2.02	1.04	50.9	21.1%
A+A+B 2-	675	YD6	2.7	1.1	2.80	0.76	56.0	10.5%
	Average		**2.0**	**1.4**	**2.72**	**0.90**	**57.1**	**17.1%**

Table 30 contains the results of the yaw damping manoeuvres performed during open road testing of the A+B3 innovative combination.

Table 30. A+B3 File:1758

Vehicle	File	Test	Steer (max)	Steer (freq)	YawB6 (peak1)	YawB6 (peak2)	SPEED (km/h)	YDC
A+B3	1602	YD1	1.6 deg	1.5 Hz	0.76	0.36	-	12.0%
A+B3	1618	YD2	1.4 deg	2.0 Hz	0.98	0.51	-	10.2%
A+B3 18	05	YD3	1.5 deg	2.2 Hz	1.61	1.03	74.5	7.0%
A+B3 18	10	YD4	1.6 deg	1.8 Hz	3.35	0.59	73.5	26.6%

	Average	**1.6 deg**	**1.8 Hz**	**1.88**	**0.68**	**74.0**	**14.6%**

Figure 42 shows the power spectral density plot of steering input for each vehicle. In all cases the dominant steering frequency is around 0.25 – 0.3 Hz, which is a low level of steering activity representing a driver comfortably in control of the vehicle.

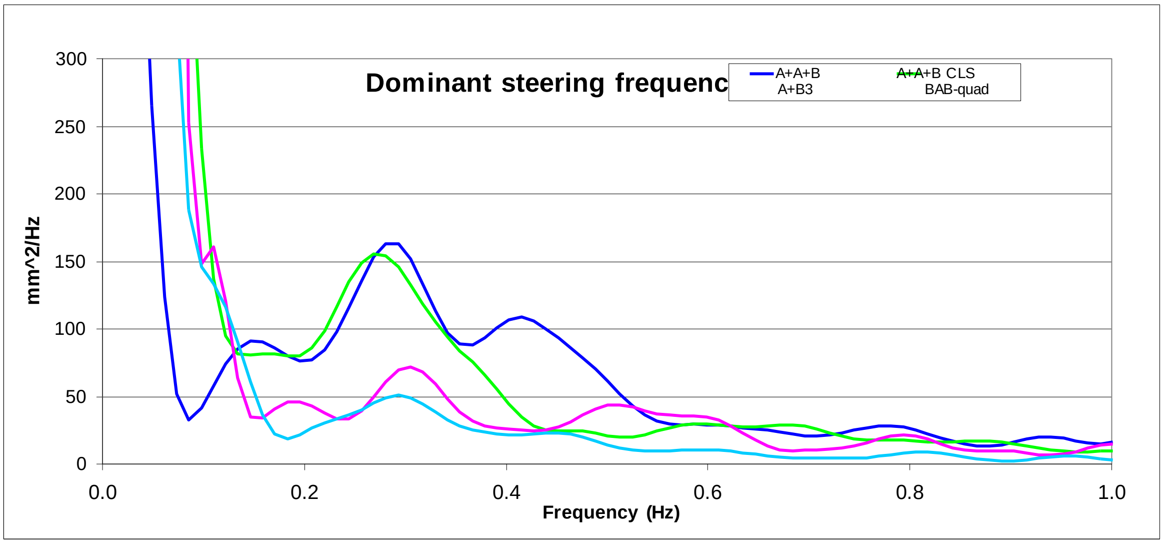

Figure 42. Power spectral density of steering input for innovative vehicles

Figure 43 shows the lateral acceleration gain for each of the innovative vehicles. The A+A+B and A+B3 vehicles demonstrated peak lateral acceleration gain at around 1.55 to 0.6 Hz, while the BAB-quad demonstrated a peak at around 0.4 Hz. It can be seen that the peak lateral acceleration gain of each vehicle occurs at a frequency which is well-separated from the driver's dominant steering frequency. Therefore, natural steering behaviour is not likely to induce unwanted dynamic behaviour in the combination.

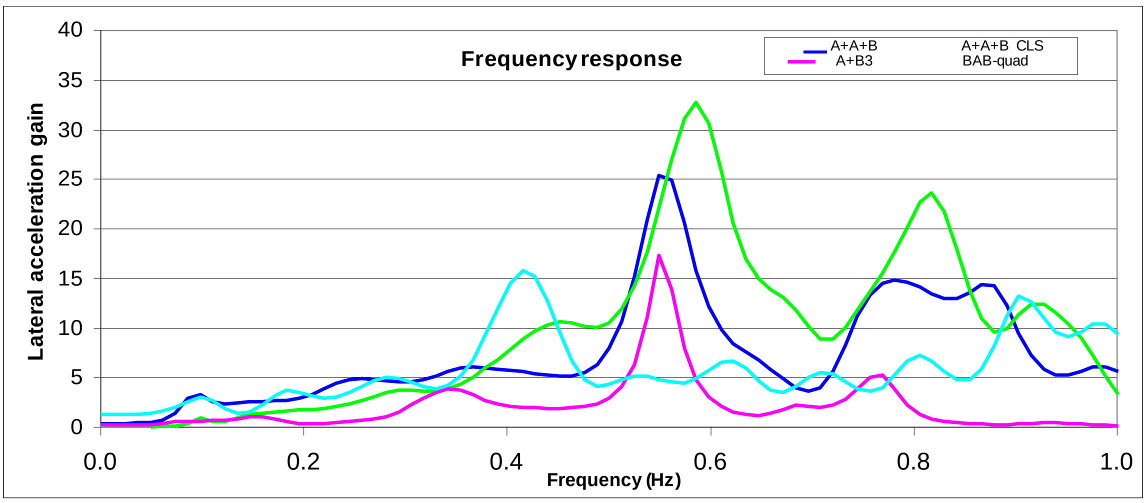

Figure 43. Lateral acceleration gain

Suspension behaviour

Roll gradient

The roll gr adient for each of the test vehicles was calcul ated based on data collected during lane change m anoeuvre t ests. The innov ative A+B3 was not instrumented to measure roll angle.

The roll gradients were:

- BAB-quad (air suspension with mechanical dolly) – 6.9 deg/g
- A+A+B standard weights (air suspension) – 2.0 deg/g
- A+A+B CLS (air suspension) – 2.5 deg/g

Figure 44 shows the roll gradient for the rear trailer of the BAB-quad combination.

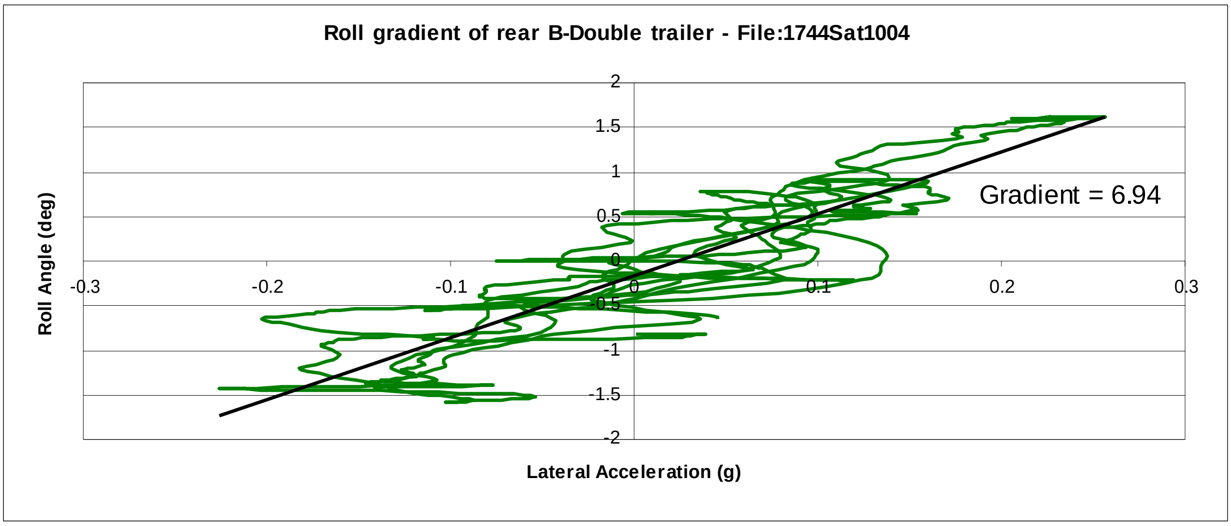

Figure 44. BAB-quad – Roll gradient of B-Double tag trailer (av.)

Figure 45 shows the roll gradient for the rear trailer of the A+A+B combination.

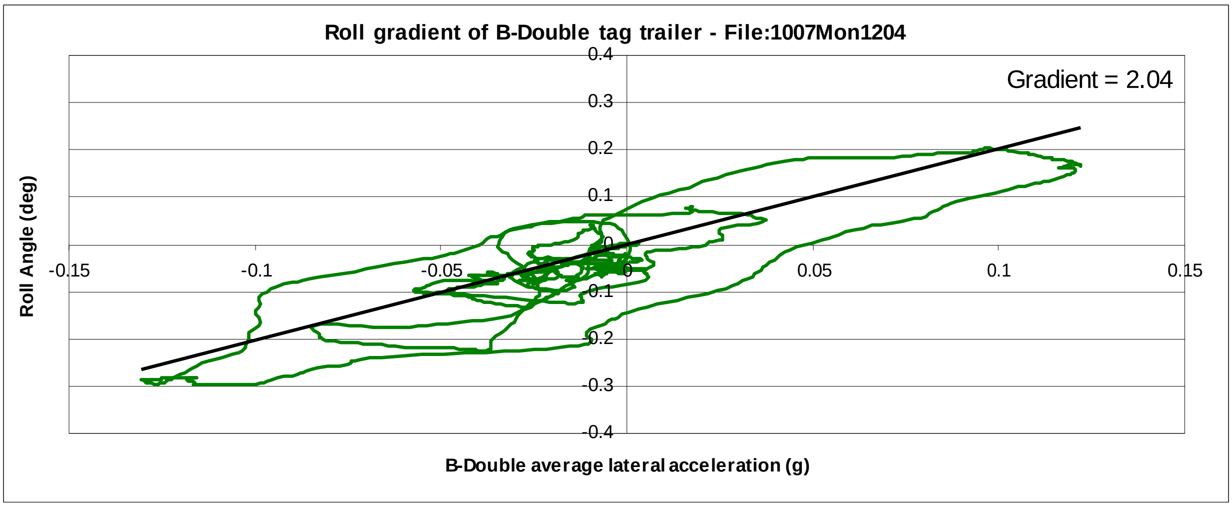

Figure 45. A+A+B – Roll gradient of B-Double tag trailer (av.)

Figure 46 shows the roll gradient for the rear trailer of the A+A+B (CLS) combination.

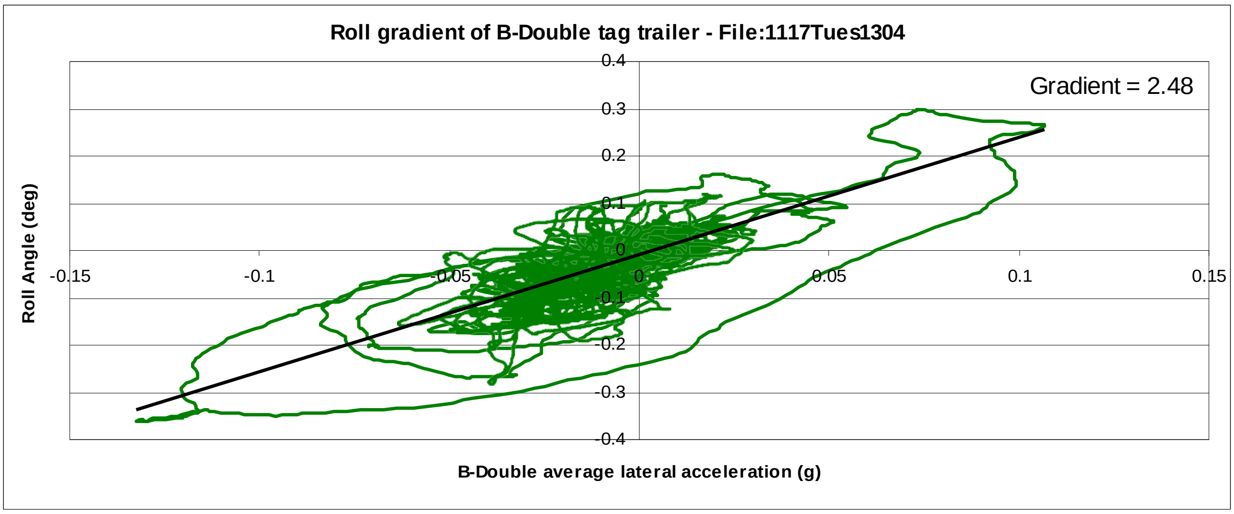

Figure 46. A+A+B (CLS) – Roll gradient of B-Double tag trailer (av.)

Model validation and calibration

Before the RATED simulation models were used to evaluate the performance of the combination vehicles, the models were validated against actual test data obtained from the Great Eastern Highway Bypass test site. Any discrepancies between the model behaviour and the test results could be removed by calibration of the models (by adjusting suspension roll stiffness, for example), so that a reliable PBS assessment could then be carried out under standard conditions.

Test conditions which often interfere with the quality of test results include:

- Road cross-fall;
- Driver steering accuracy;
- Vehicle loading; and
- Test speed.

Once the models are validated under the actual (imperfect) test conditions, they can be used to evaluate the performance of the vehicles under standard conditions (ie. flat road surface with correct driver steer input, axle loads and test speeds).

The models were used to replicate selected test manoeuvres at actual test weights, at the recorded test speeds with the measured road cross-fall applied. Driver steering error during the SAE lane change was replicated also. In all cases very good comparison was observed between the simulation models and the recorded test data, with only minor adjustments required in some cases.

Output from calibrated models

Figure 47, Figure 48, Figure 49 and Figure 50 show the comparison of lateral acceleration at the prime mover and the rear trailer for each innovative test vehicle. It can be seen that good comparisons exist between the simulation and test data, with minor adjustments of the model parameters.

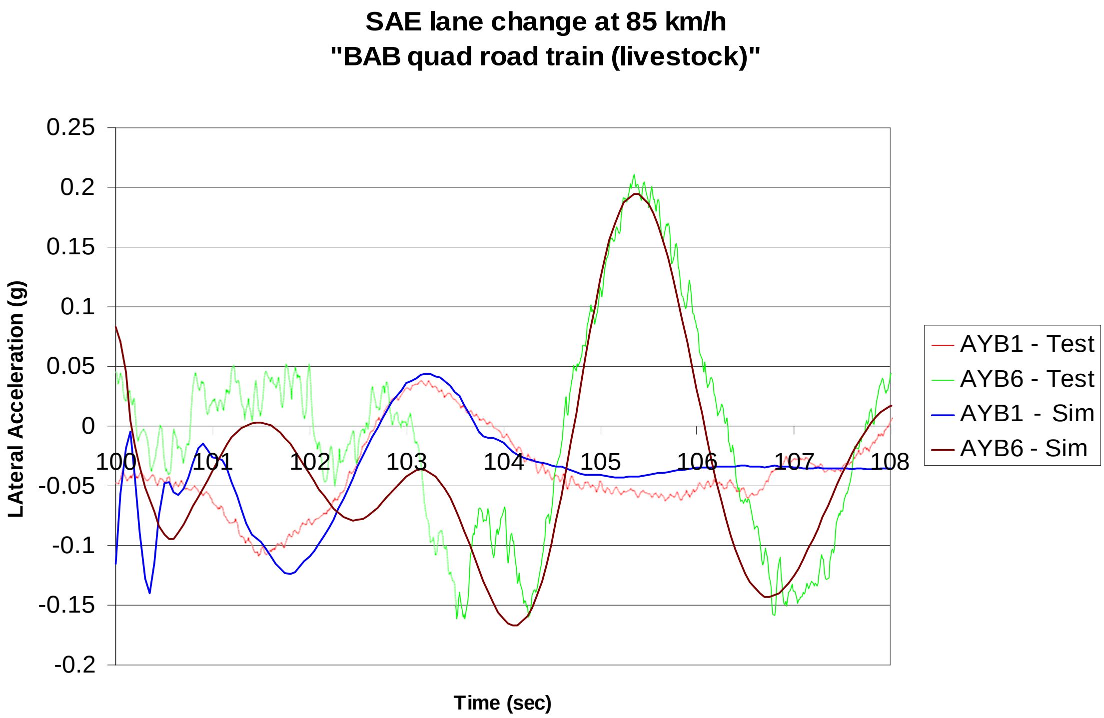

Figure 47. Comparison of test and simulation - BAB quad road train

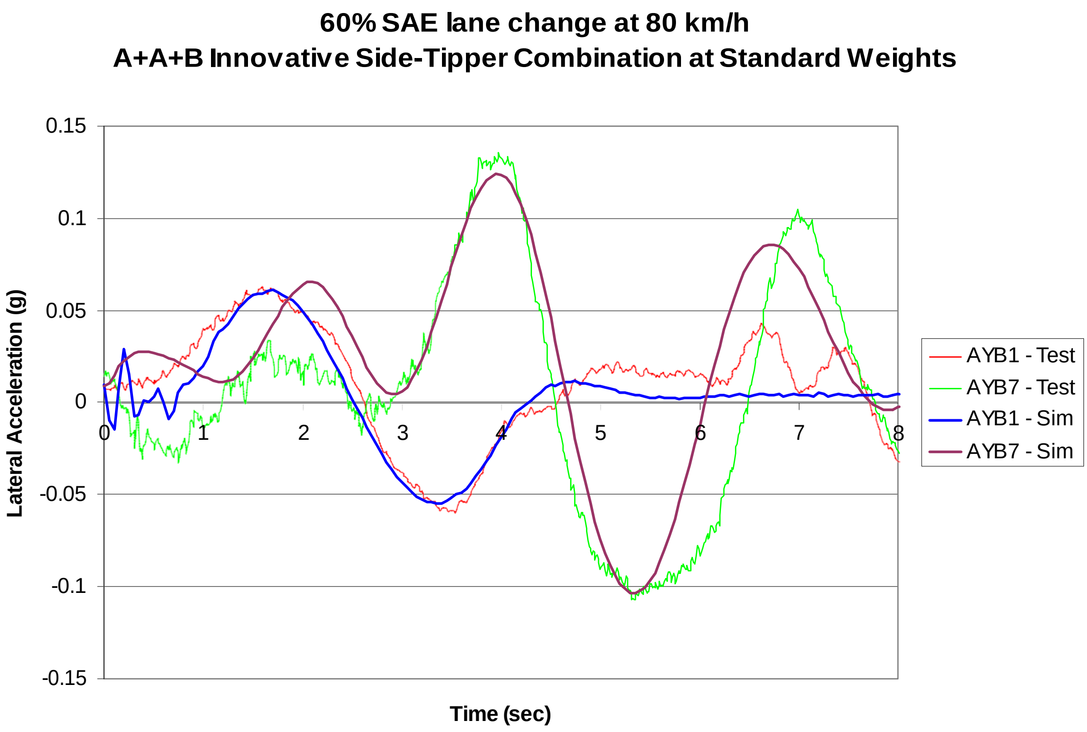

Figure 48. Comparison of test and simulation - A+A+B Standard axle loads

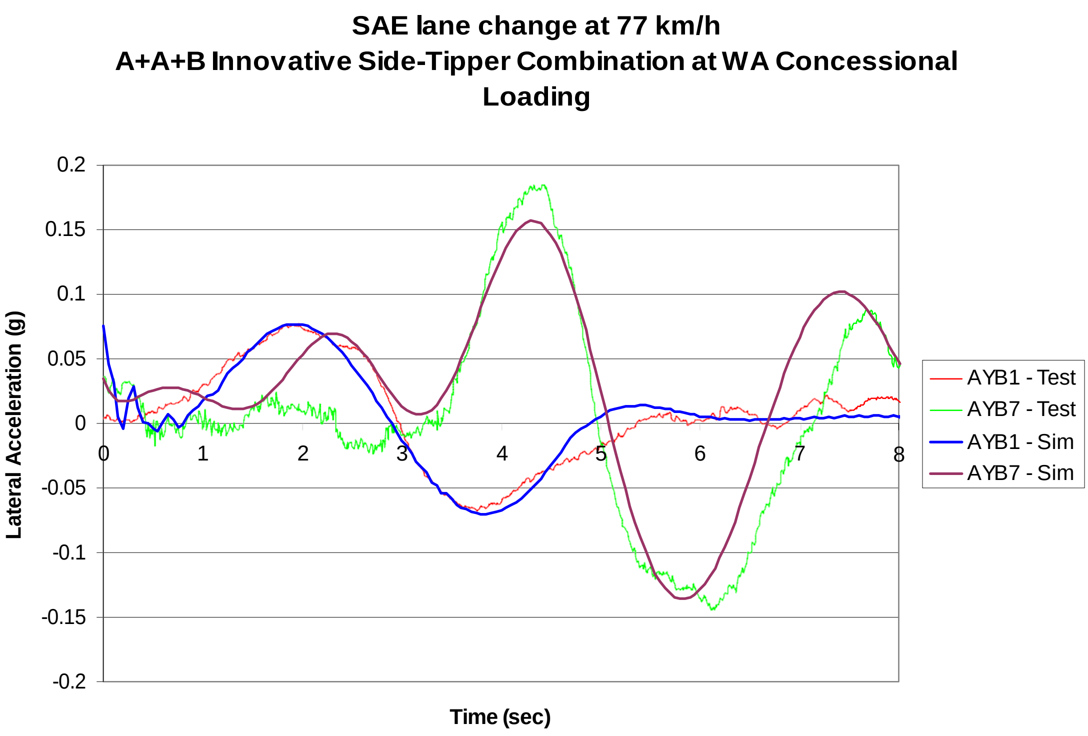

Figure 49. Comparison of test and simulation - A+A+B con cessional axle loads

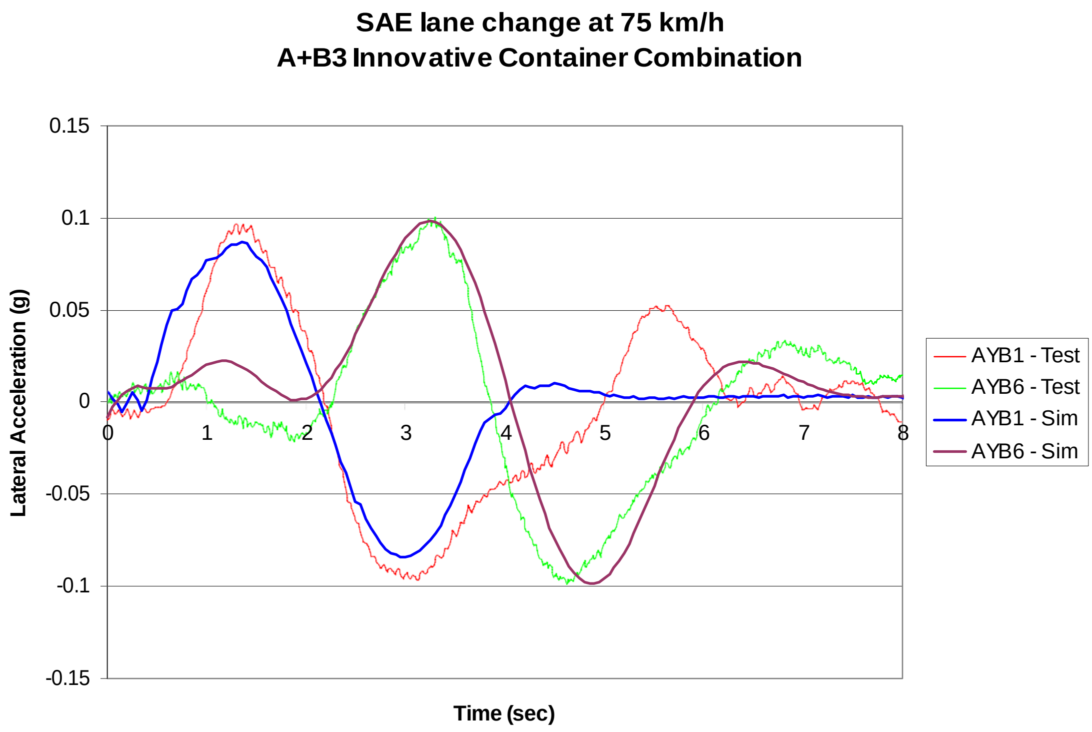

Figure 50. Comparison of test and simulation – A+B3 quad road train

Performance comparisions using simulation

Using the models calibrated against the test data, the three combination vehicles were evaluated for the following Performance-Based Standards:

- Tracking Ability on a Straight Path (TASP);
- Static Rollover Threshold (SRT);
- Rearward Amplification (RA);
- High-Speed Transient Offtracking (HSTO); and
- Yaw Damping Coefficient (YDC).

The performance of the vehicles evaluated against Level 4 PBS is summarised in Table 31.

Table 31. Performance of innovatives evaluated against Level 4 PBS measures

PBS measure	Performance target (Level 4)	BAB quad (livestock)	A+A+B (side tipper) Standard weight	A+A+B (side tipper) concessional weight	A+B3 (container)
TASP	≤ 3.30 m	2.97 m 3 2.90	m 3 2.99	m 3 2.96	m 3
SRT	≥ 0.35 g	1st unit 0.34 g 2 2nd unit 0.32 g 2	1st unit 0.54 g 3 2nd unit 0.52 g 3 3rd unit 0.51 g 3	1st unit 0.50 g 3 2nd unit 0.47 g 3 3rd unit 0.46 g 3	1st unit 0.36 g 3 2nd unit 0.35 g 3
RA	≤ (5.70 × SRTrrcu*)	1.66 3 2.47	3 2.73	2 1.05	3
HSTO	≤ 1.20 m	1.35 m x	1.35 m 2 1.94	m 2 0.80	m 3
YDC	≥ 0.15	0.31 3 0.14	2 0.08	2 0.36	3

Table 31 shows the differences in performance between the four innovative vehicles. The differences in SRT can be attributed to the different body types on each vehicle. The A+A+B combinations had tipper bodies with low COG heights, while the BAB with livestock bodies and the A+B3, with containers had considerably higher COG heights.

The A+A+B combinations were seen to exhibit the worst high speed dynamic results. The A+B3 on the other hand, had excellent high-speed dynamic performance for a combination vehicle of its size and mass. This vehicle had virtually no RA, and easily satisfied HSTO and YDC, with performance figures closer to that of a much shorter combination.

APPENDIX B Supplementry data

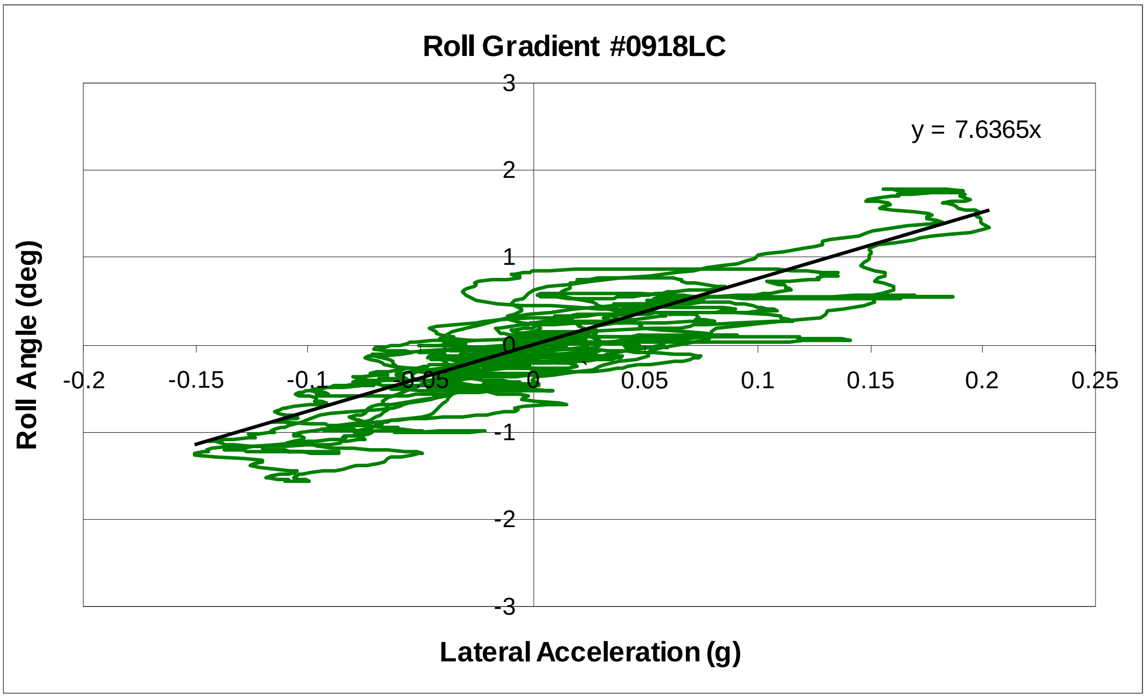

Figure 51. Air/mech combination roll gradient

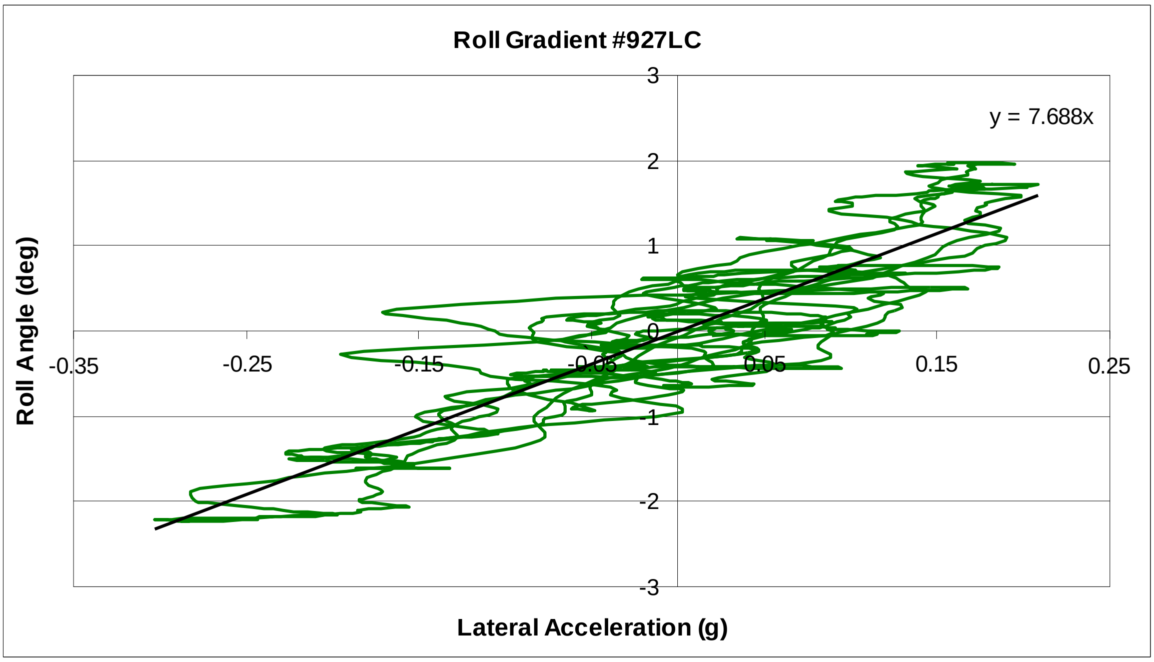

Figure 52. All air combination roll gradient

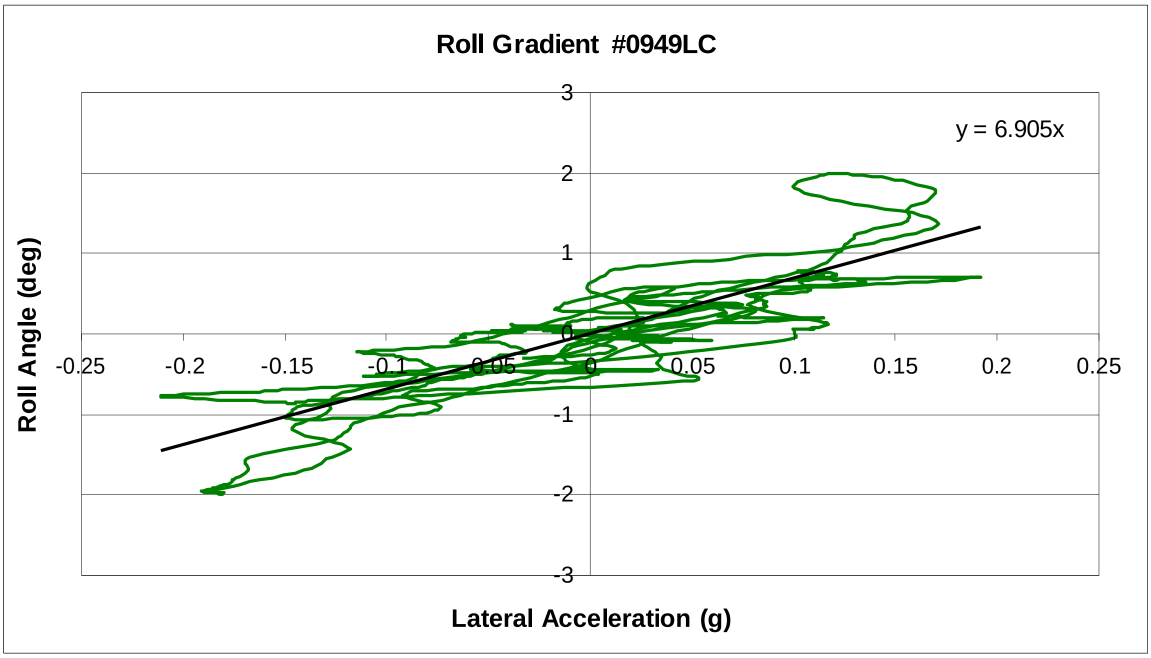

Figure 53. All mech combination roll gradient

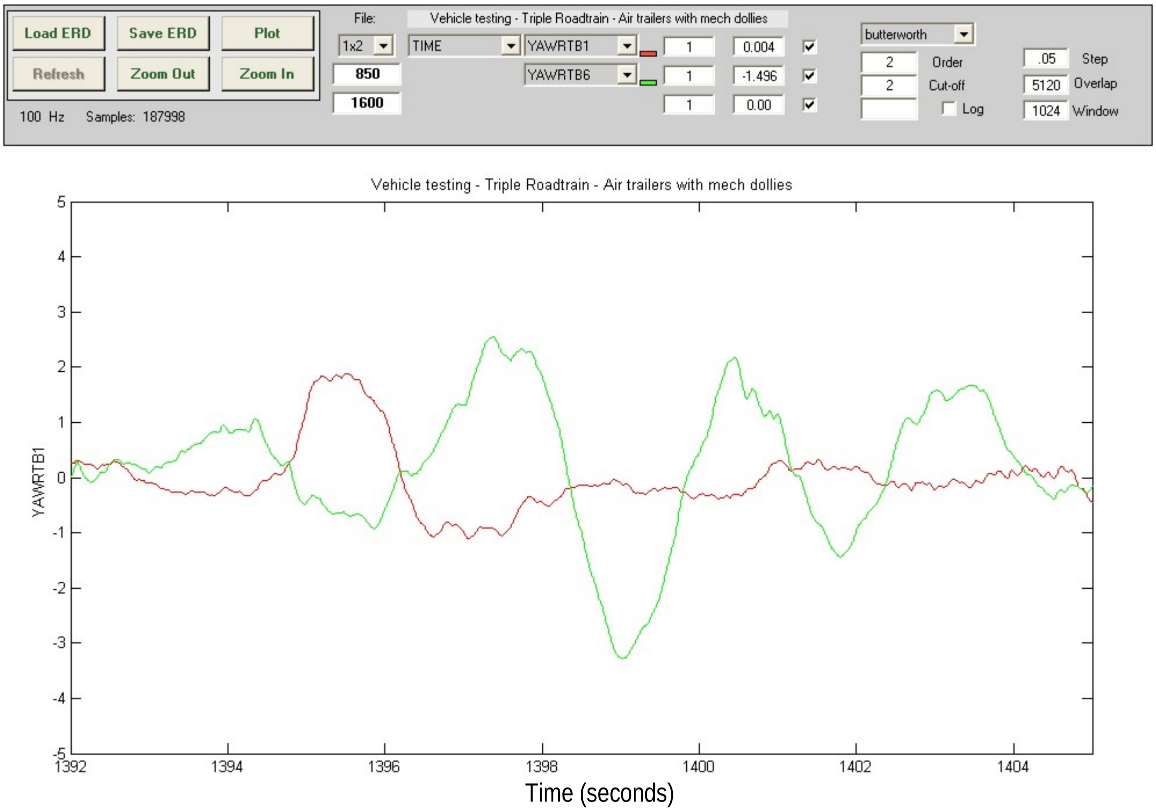

Figure 54. Vehicle 1 – 703 Route Testing- Yaw Damping 1

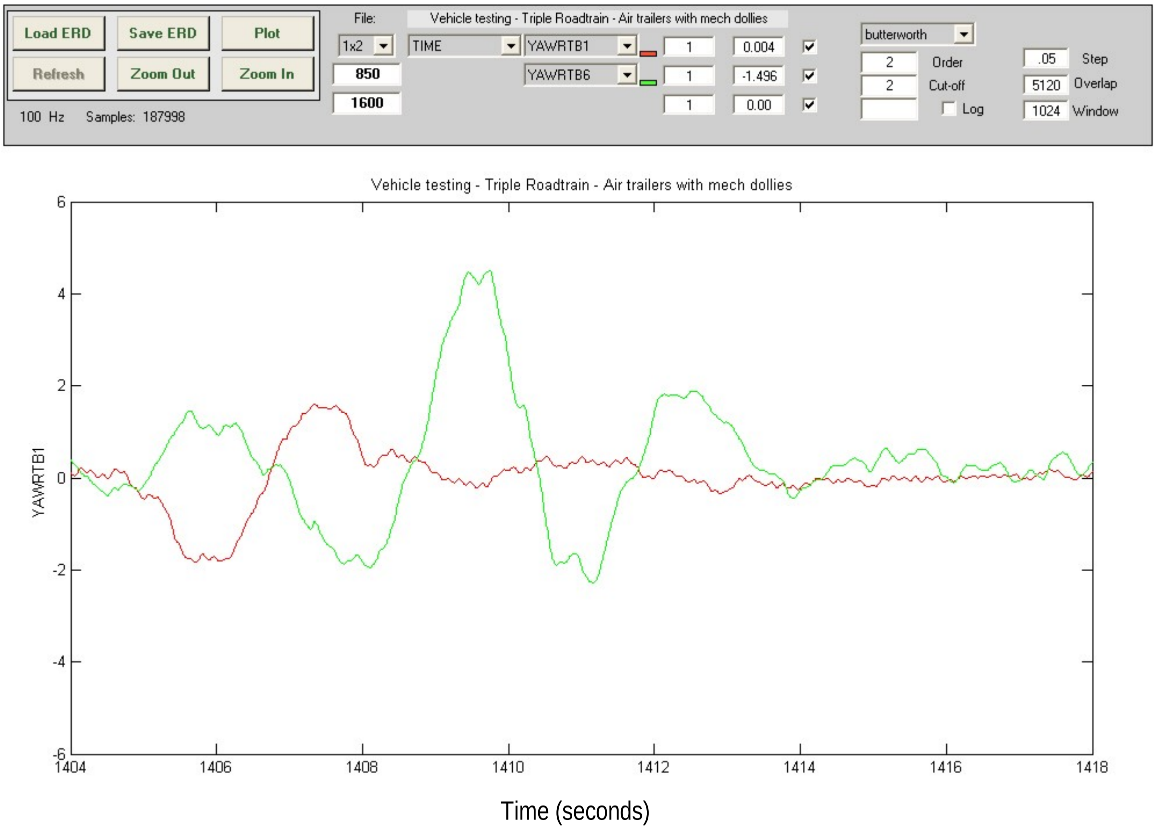

Figure 55. Vehicle 1 – 703 Route Testing- Yaw Damping 2

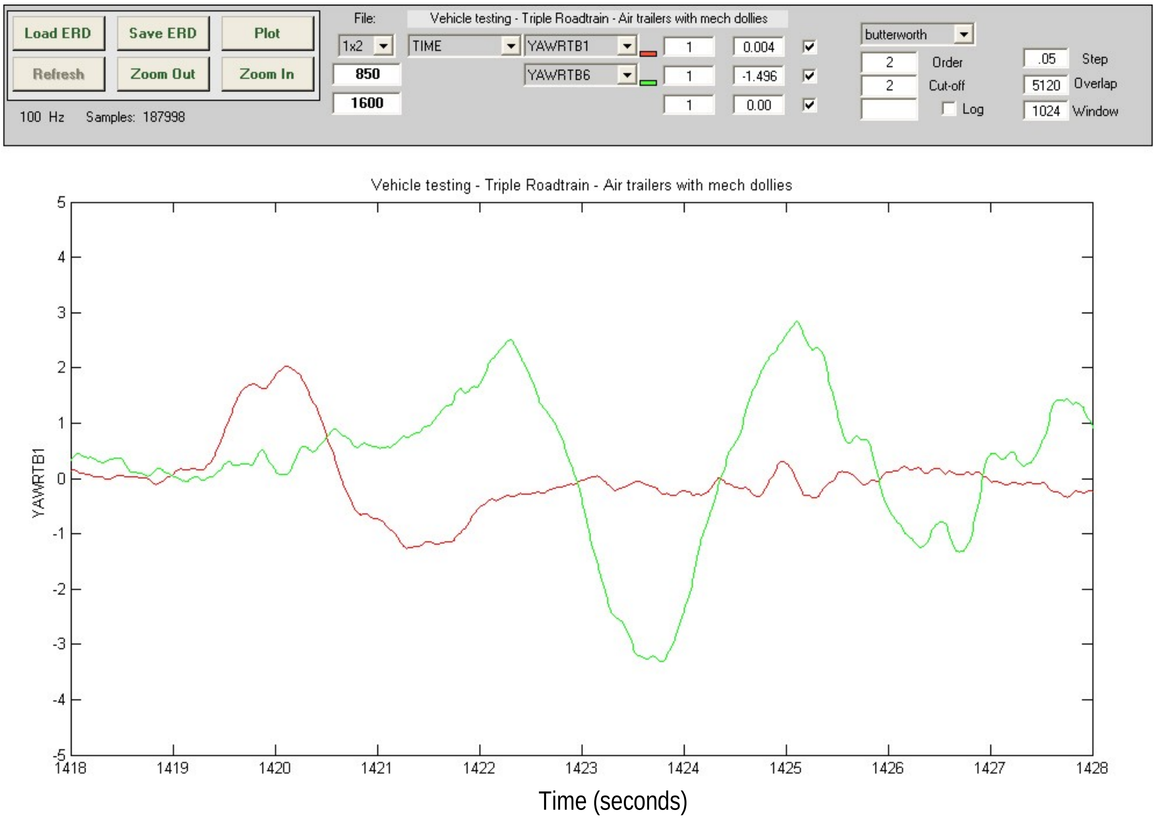

Figure 56. Vehicle 1 – 703 Route Testing- Yaw Damping 3

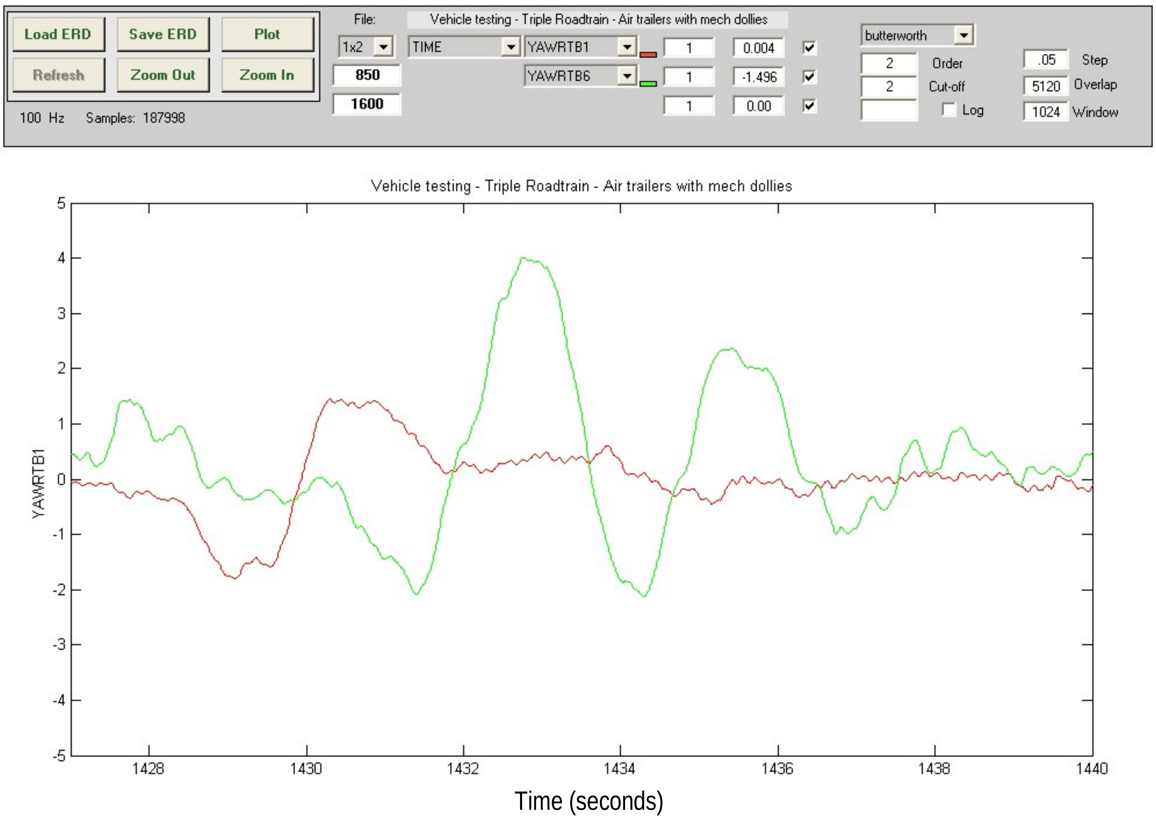

Figure 57. Vehicle 1 – 703 Route Testing- Yaw Damping 4

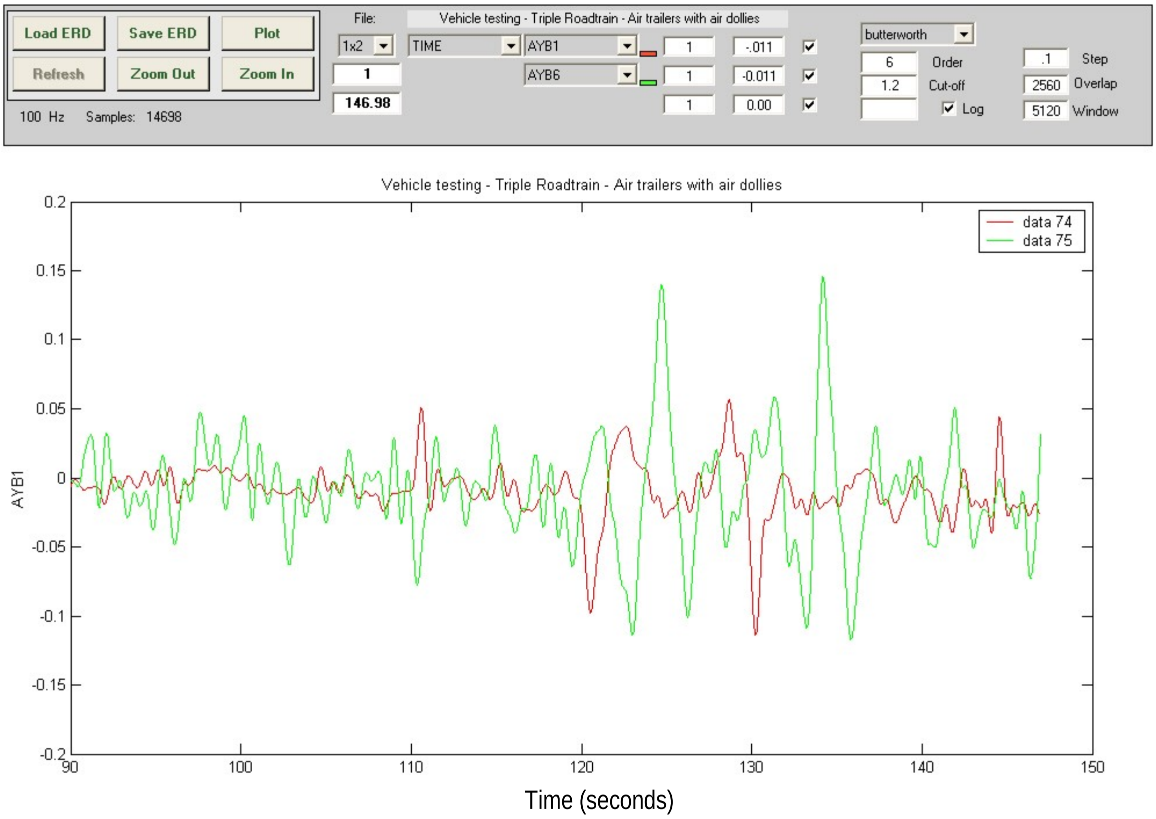

Figure 58. Vehicle 2 – 844 Lane Change

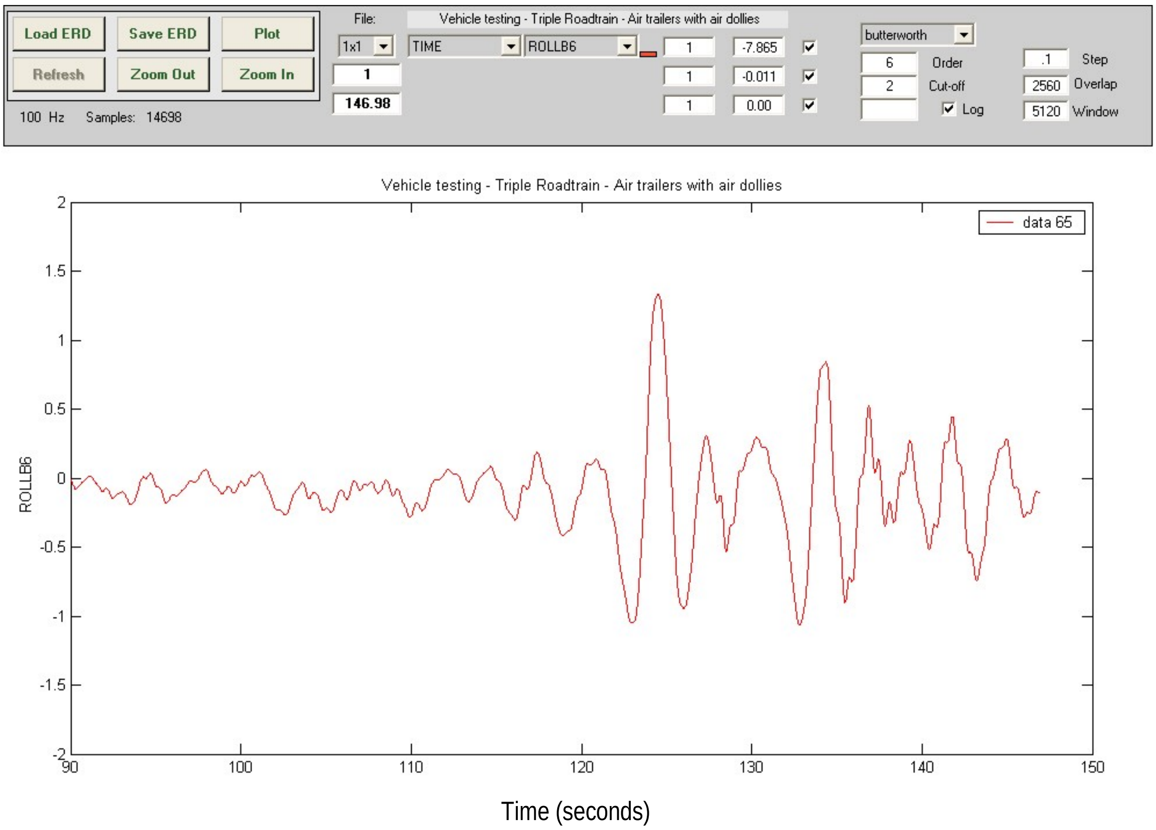

Figure 59. Vehicle 2 – 844 Lane Change - Roll Angle

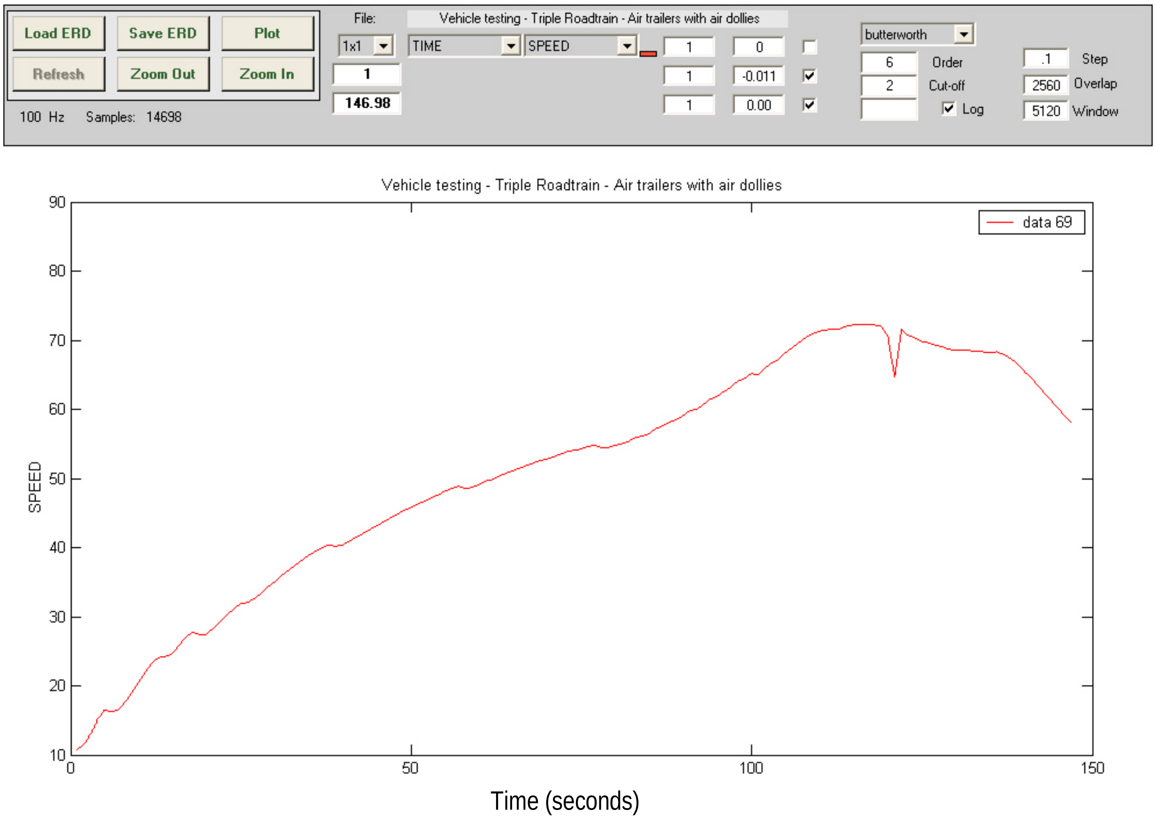

Figure 60. Vehicle 2 – 844 Lane Change - Speed

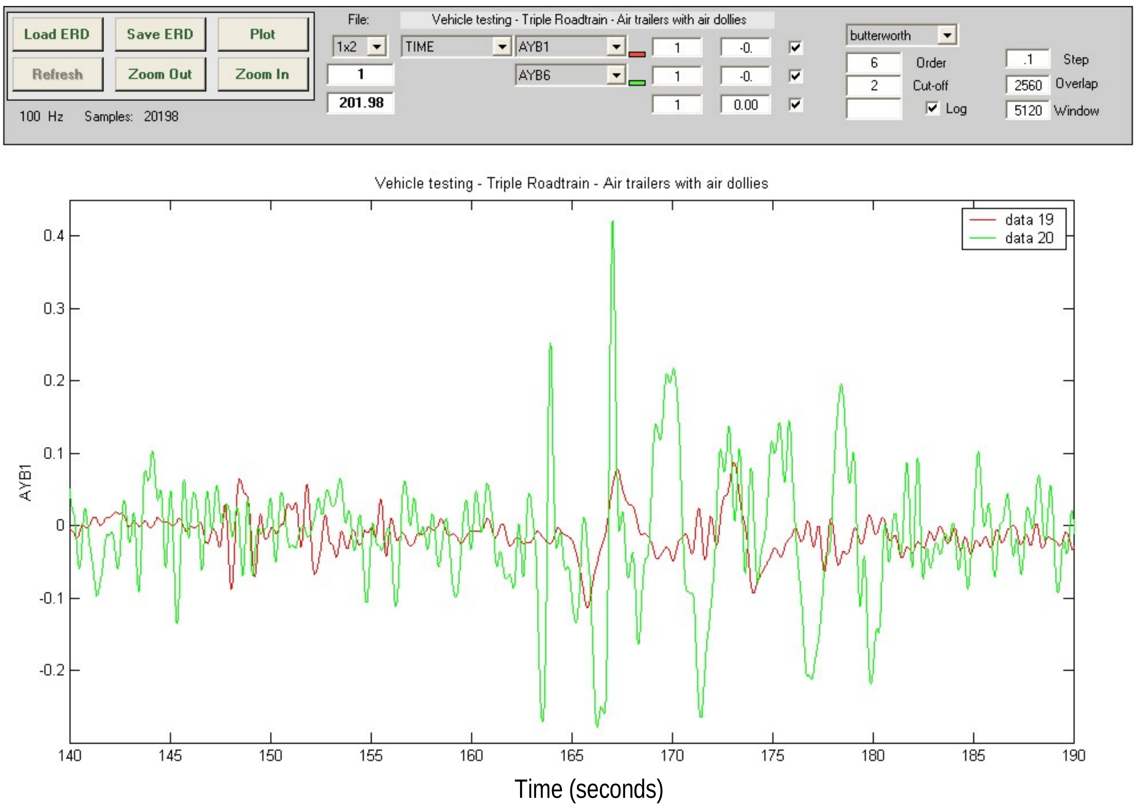

Figure 61. Vehicle 2– 906 Lane Change

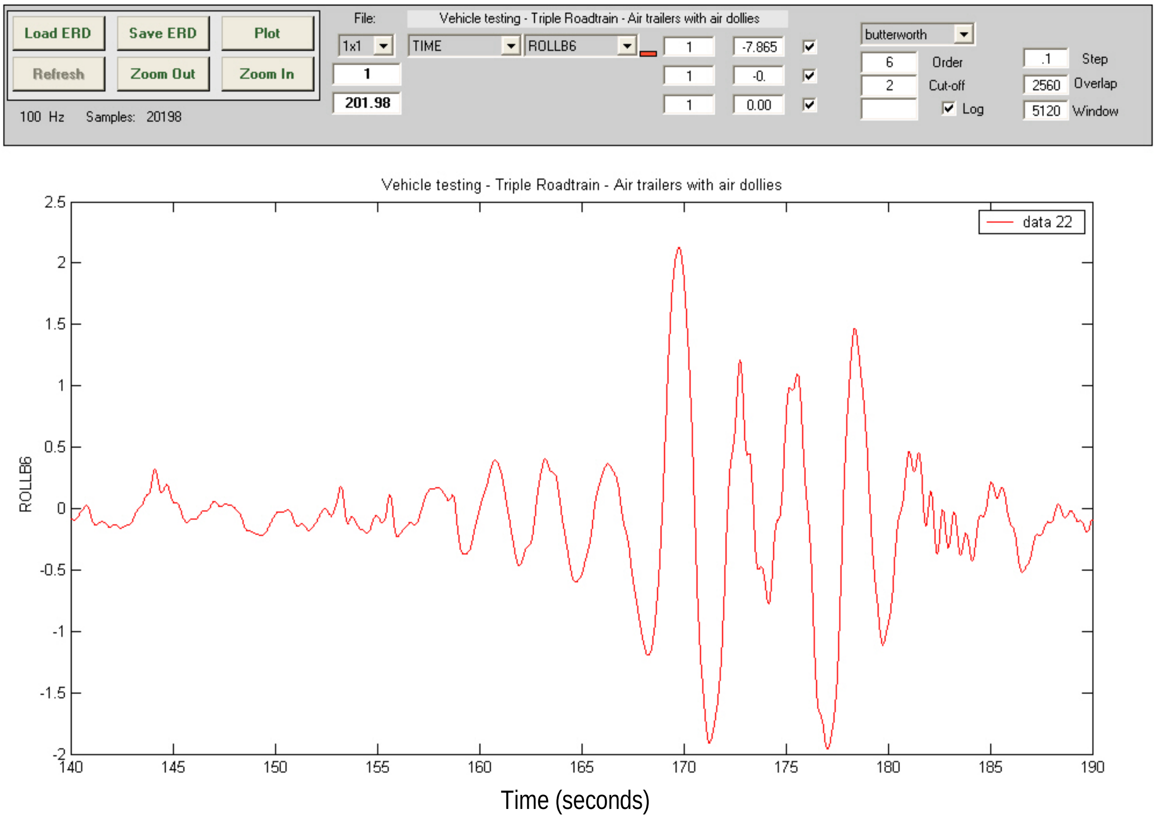

Figure 62. Vehicle 2 – 906 Lane Change – Roll Angle

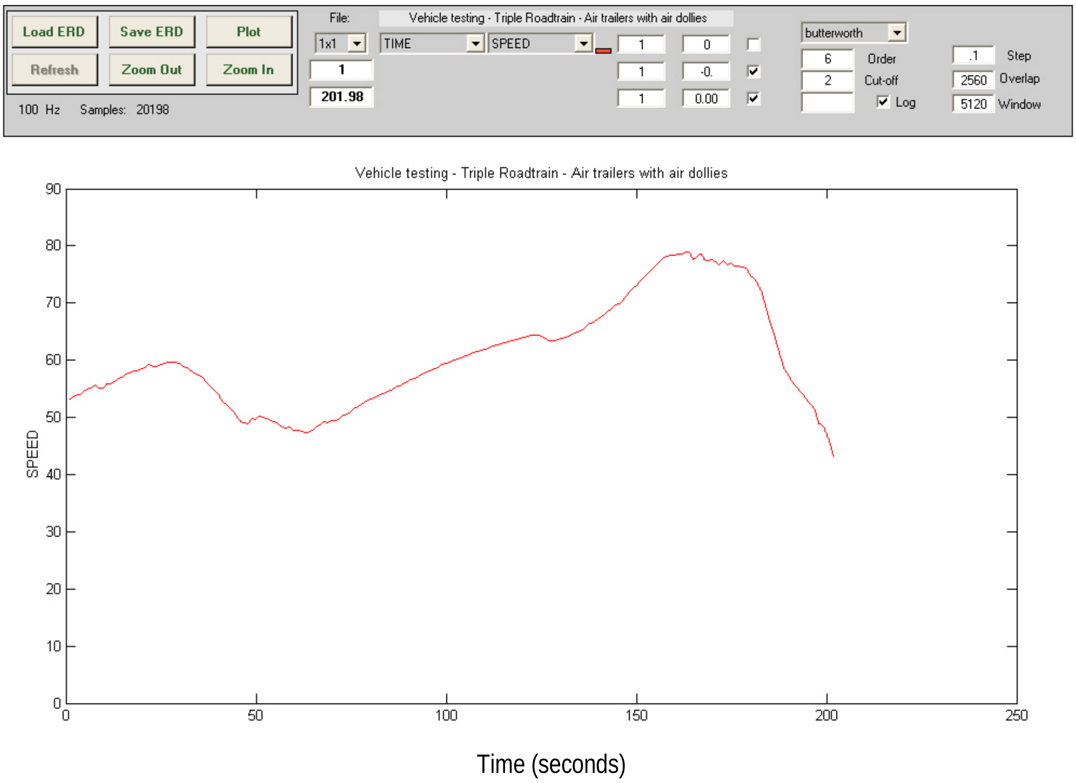

Figure 63. Vehicle 2 – 906 Lane Change - Speed

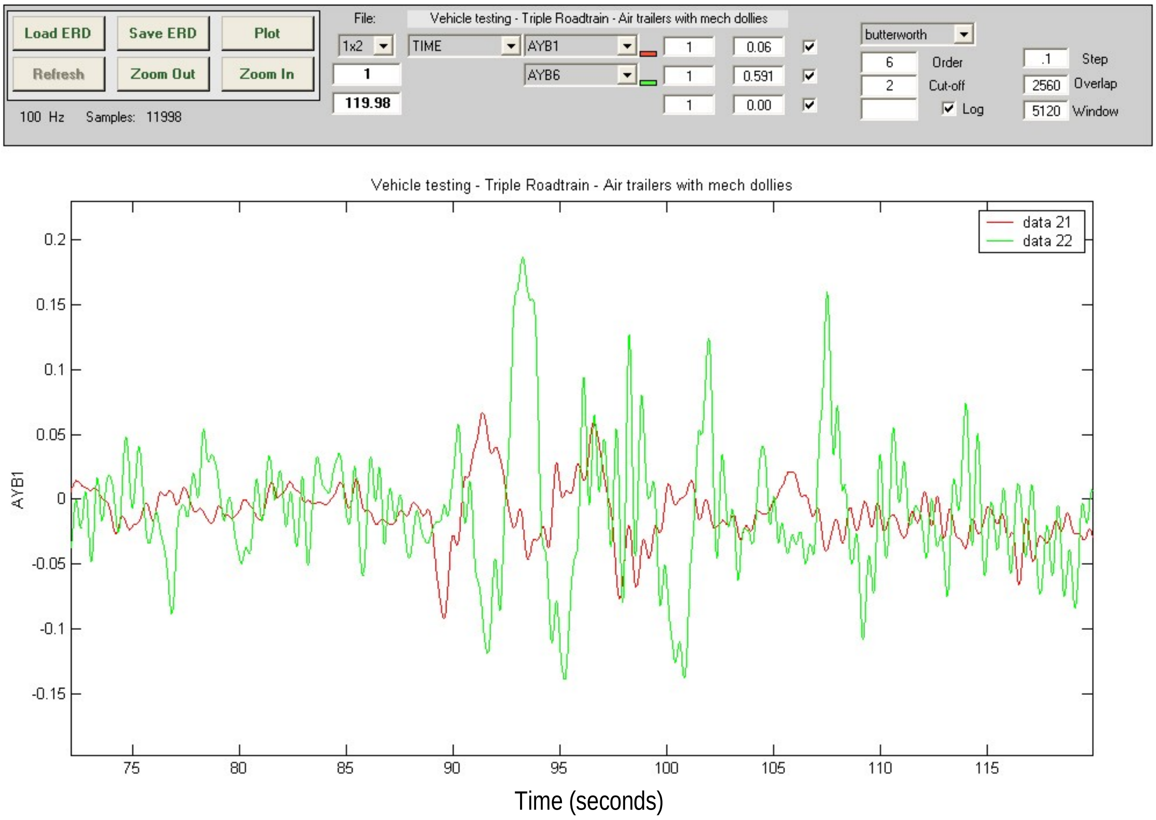

Figure 64. Vehicle 1 – 918 Lane Change

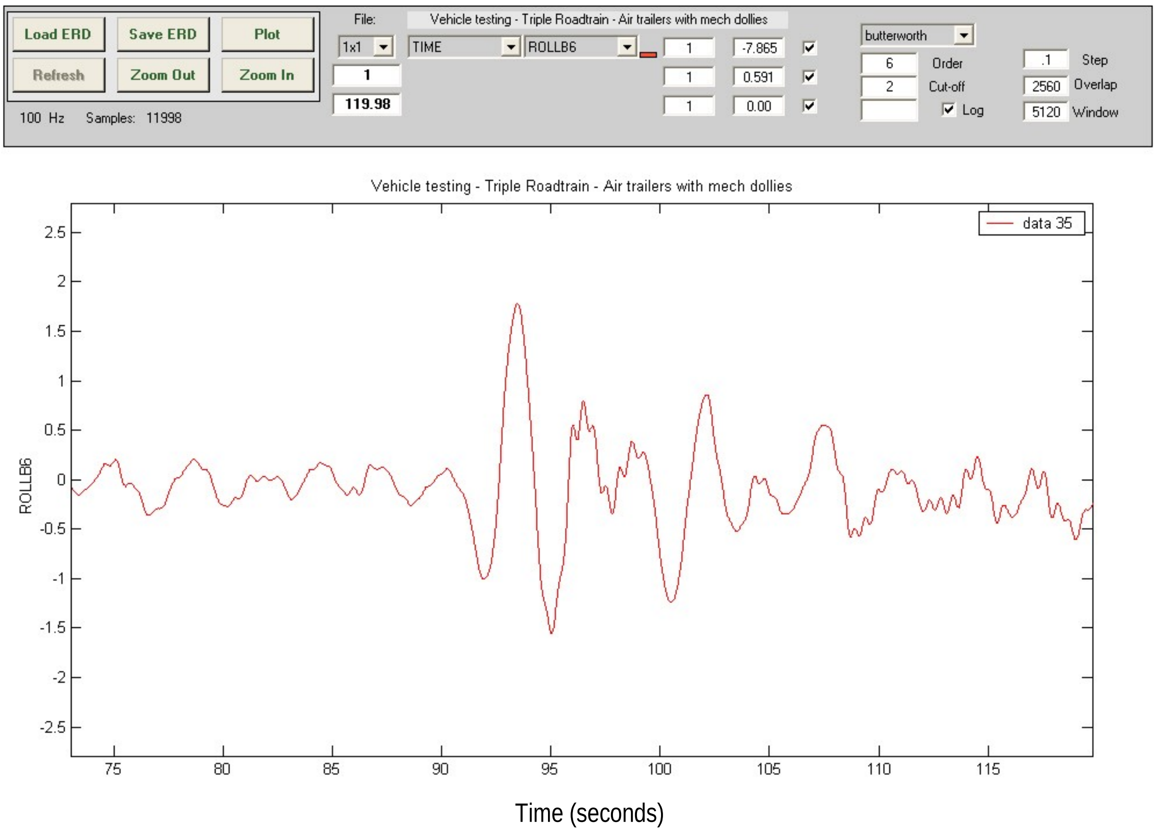

Figure 65. Vehicle 1 – 918 Lane Change – Roll Angle

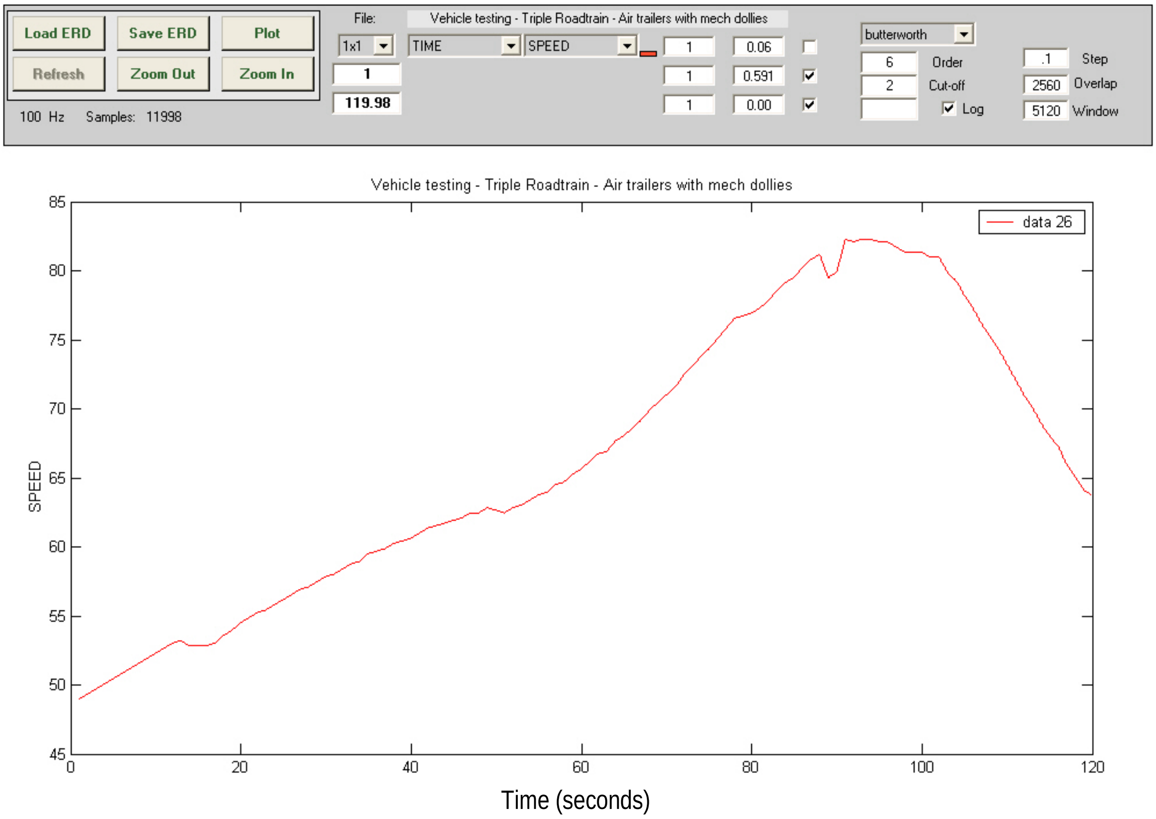

Figure 66. Vehicle 1 – 918 Lane Change -Speed

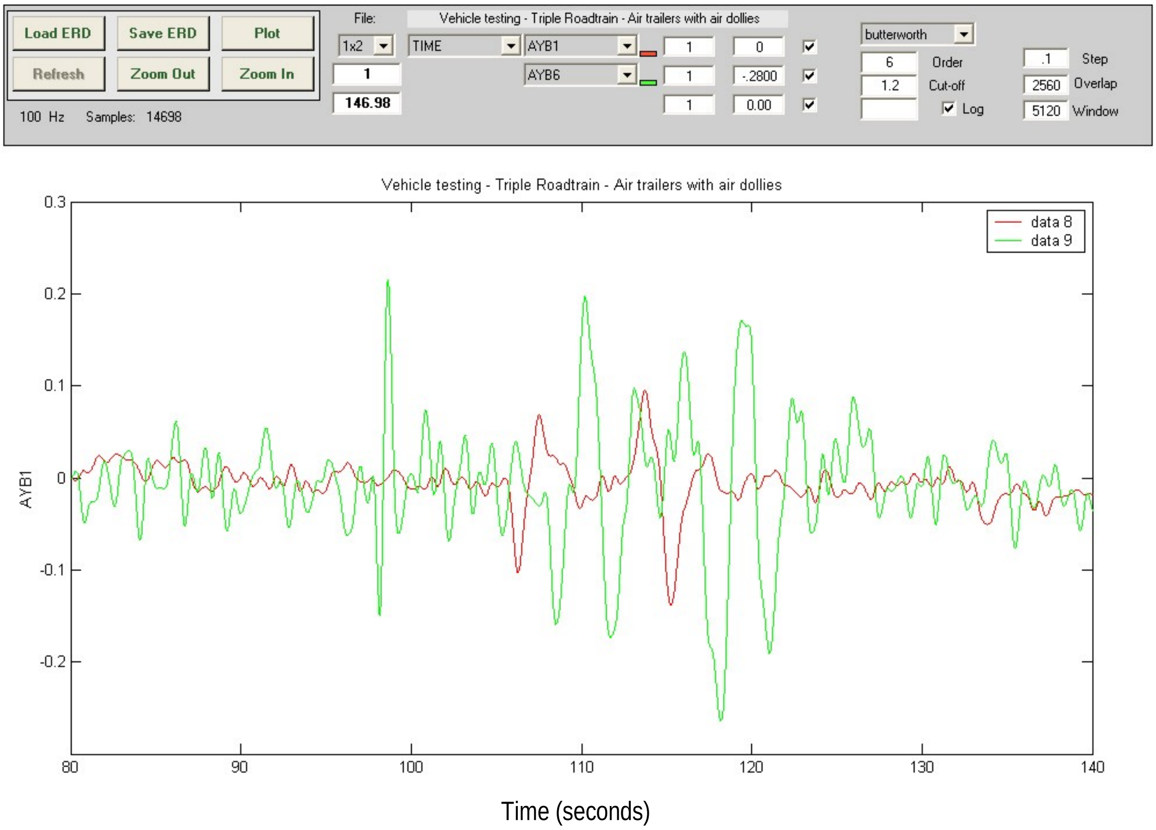

Figure 67. Vehicle 2– 927 Lane Change

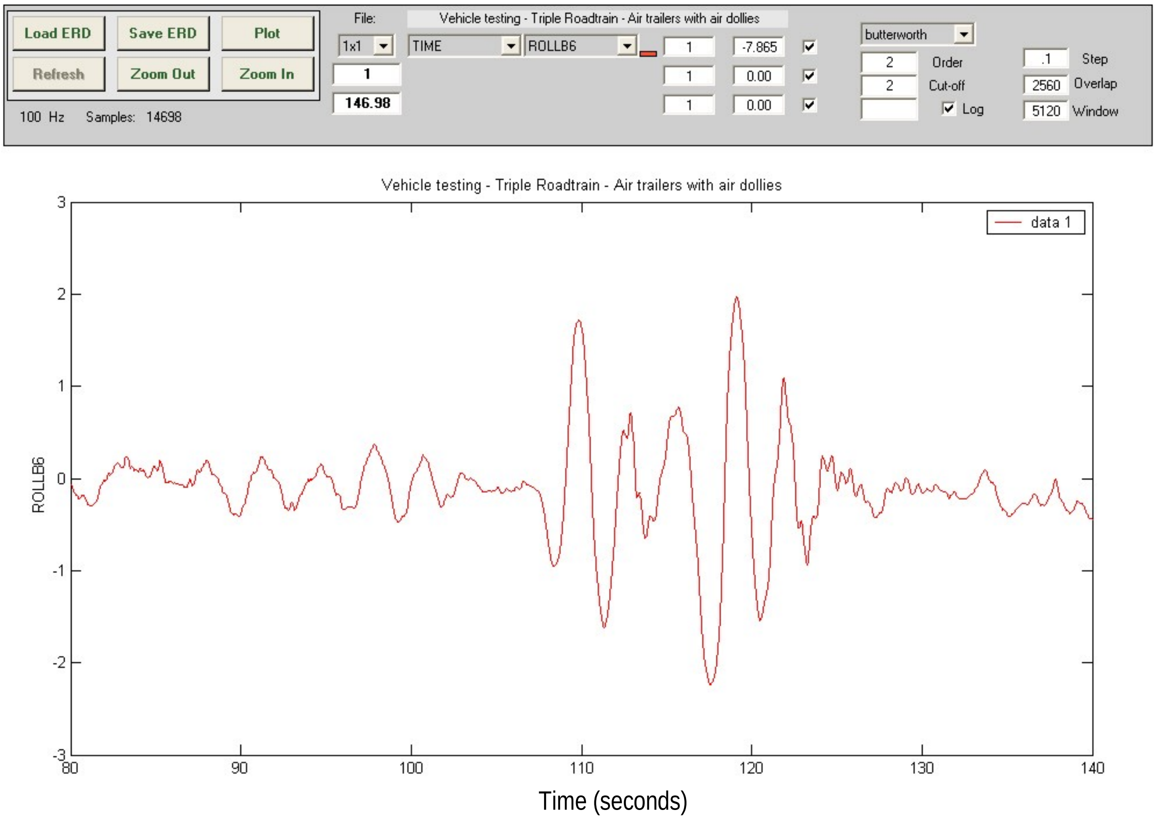

Figure 68. Vehicle 2 – 927 Lane Change – Roll Angle

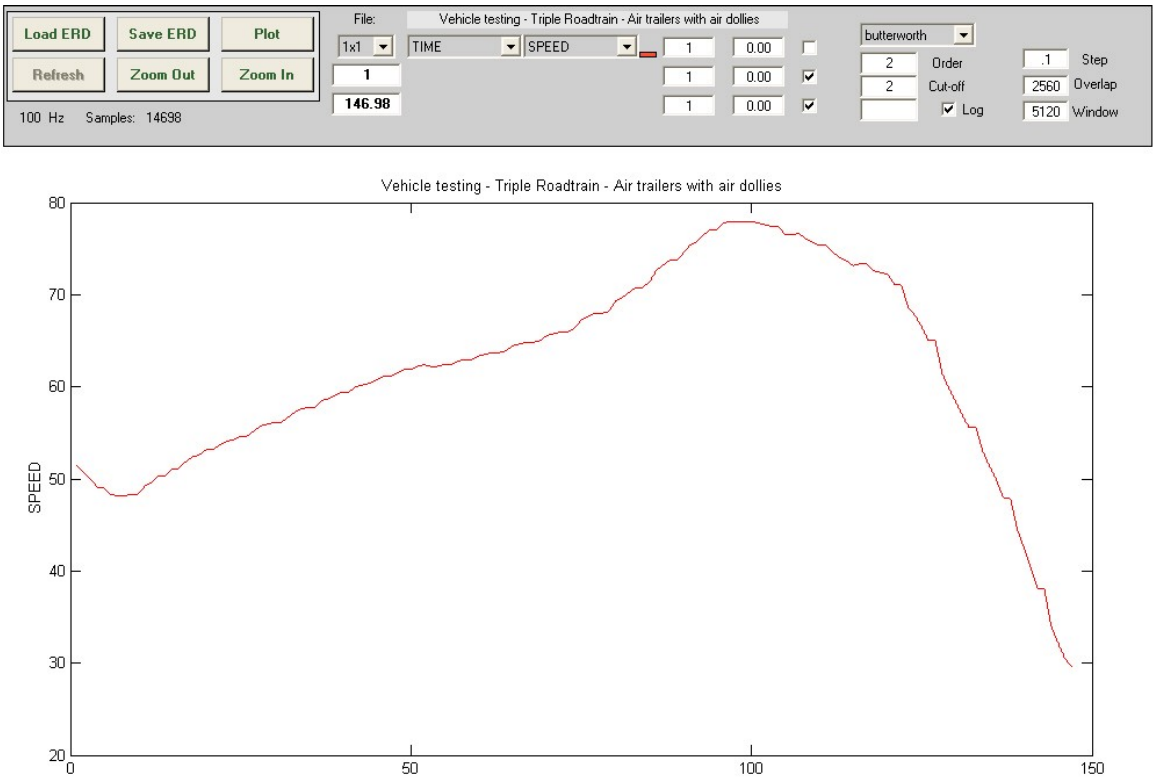

Figure 69. Vehicle 2 – 927 Lane Change - Speed

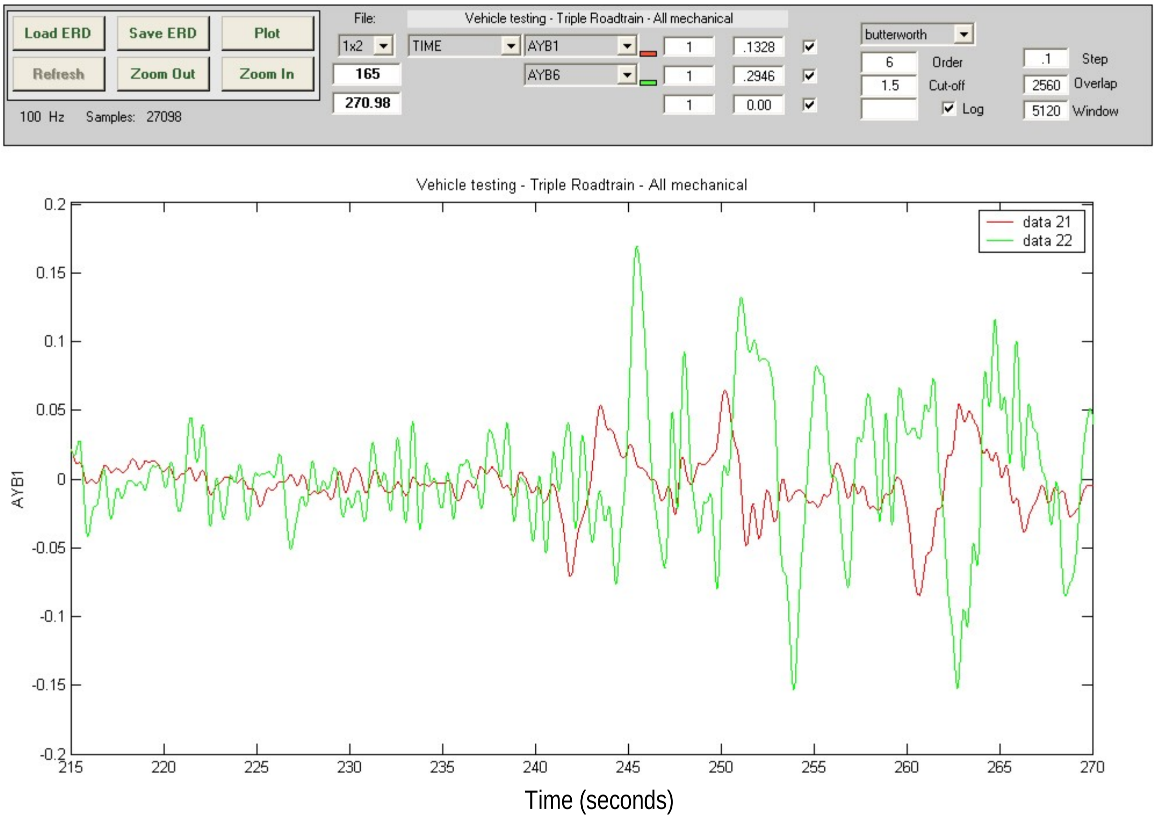

Figure 70. Vehicle 3 – 934 Lane Change

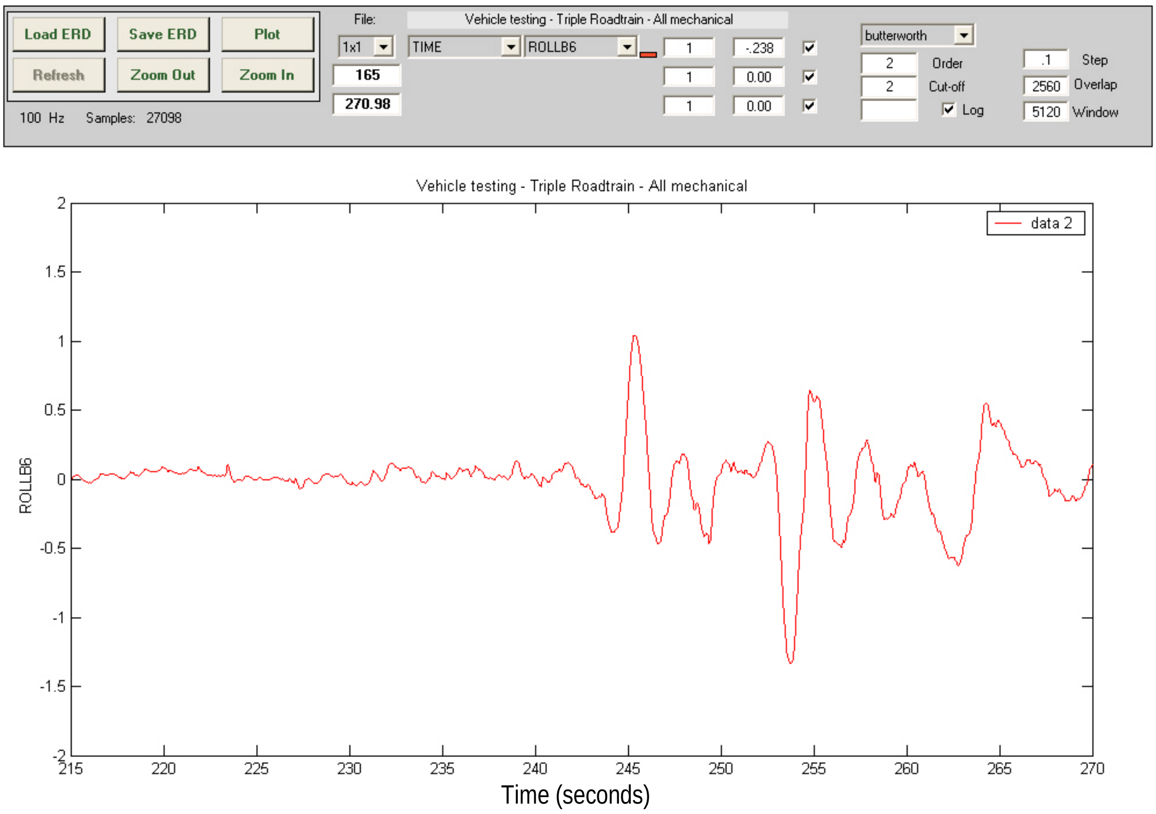

Figure 71. Vehicle 3 – 934 Lane Change – Roll Angle

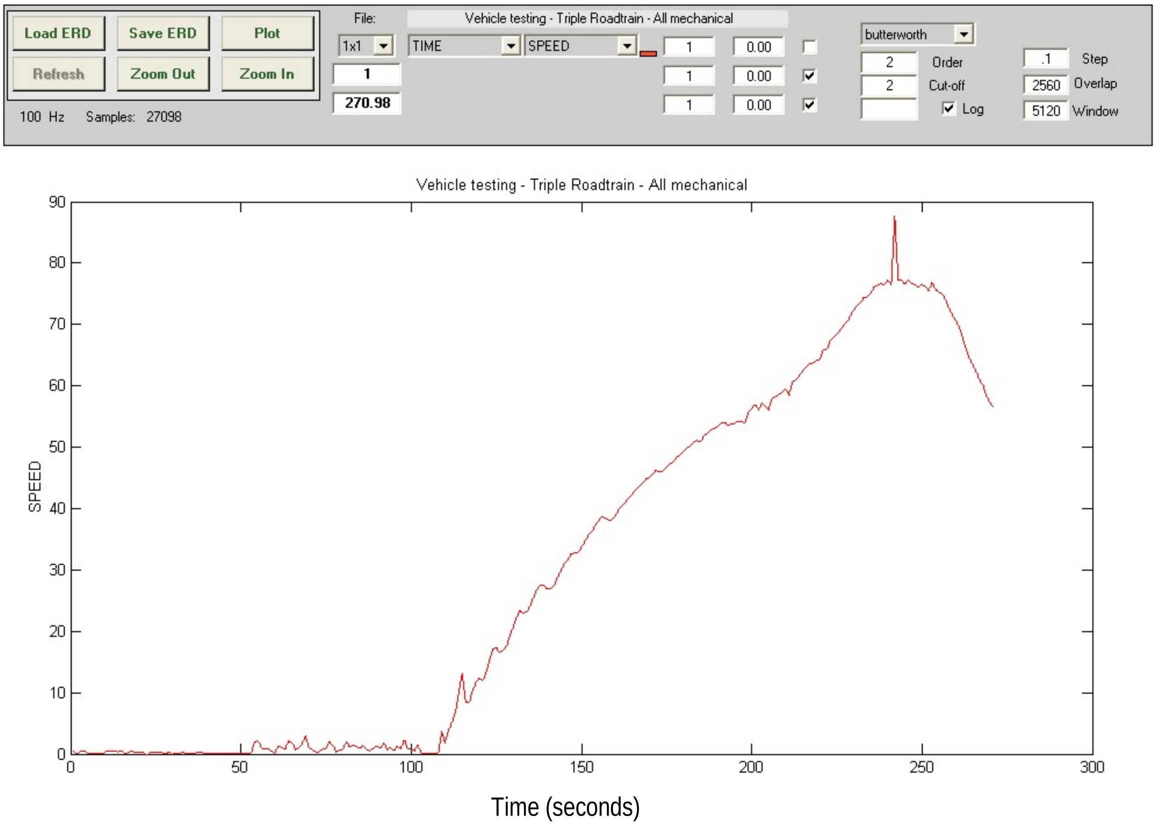

Figure 72. Vehicle 3 – 934 Lane Change – Speed

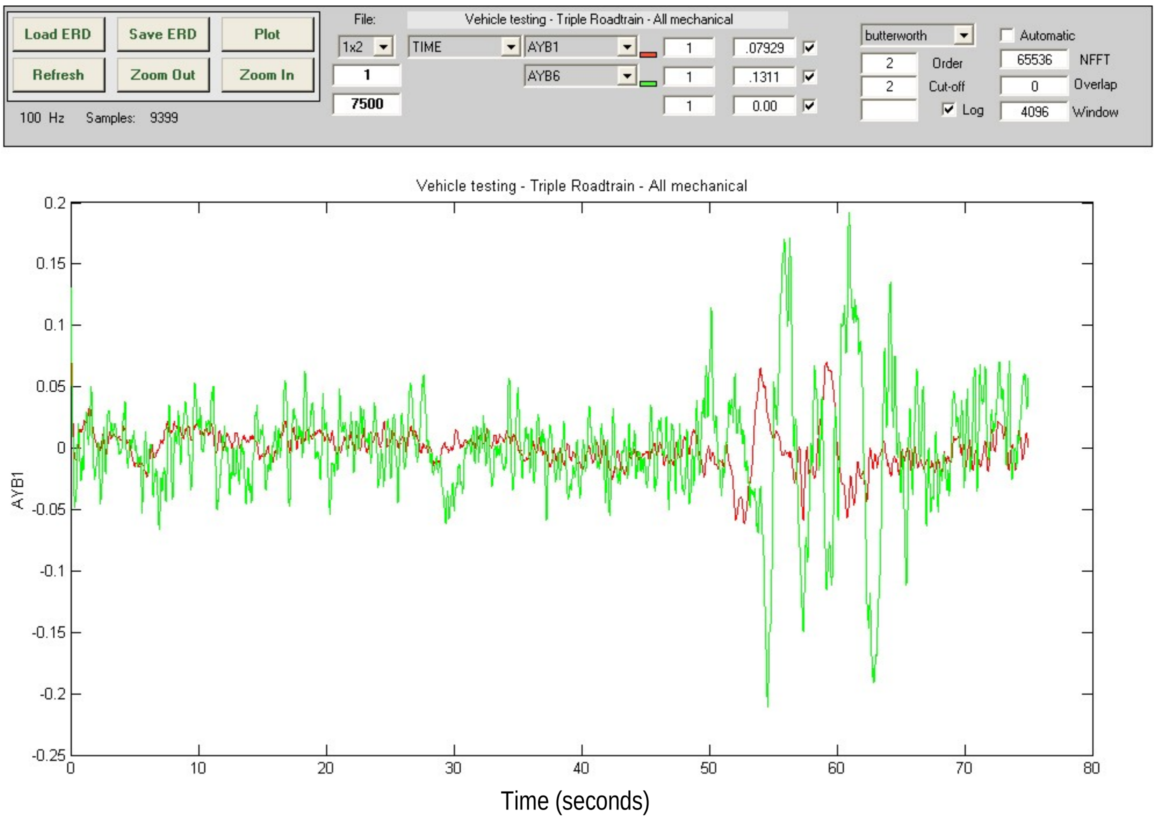

Figure 73. Vehicle 3 – 949 Lane Change

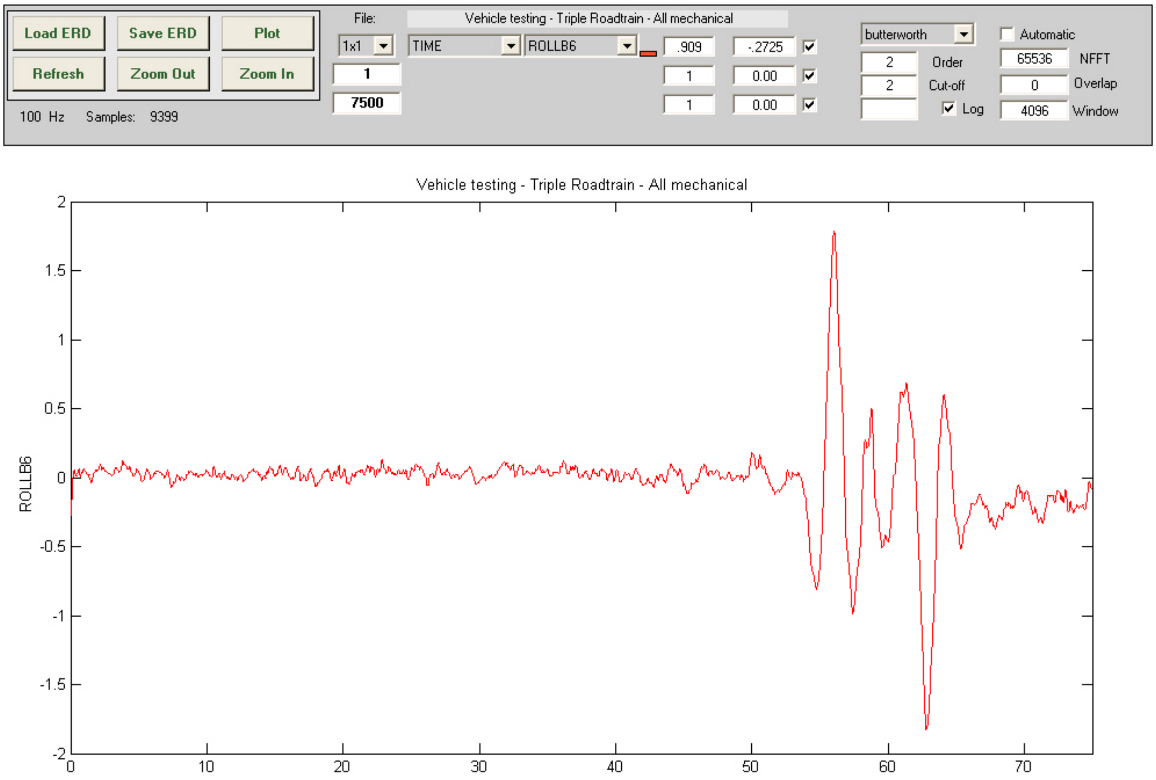

Figure 74. Vehicle 3 – 949 Lane Change - Roll

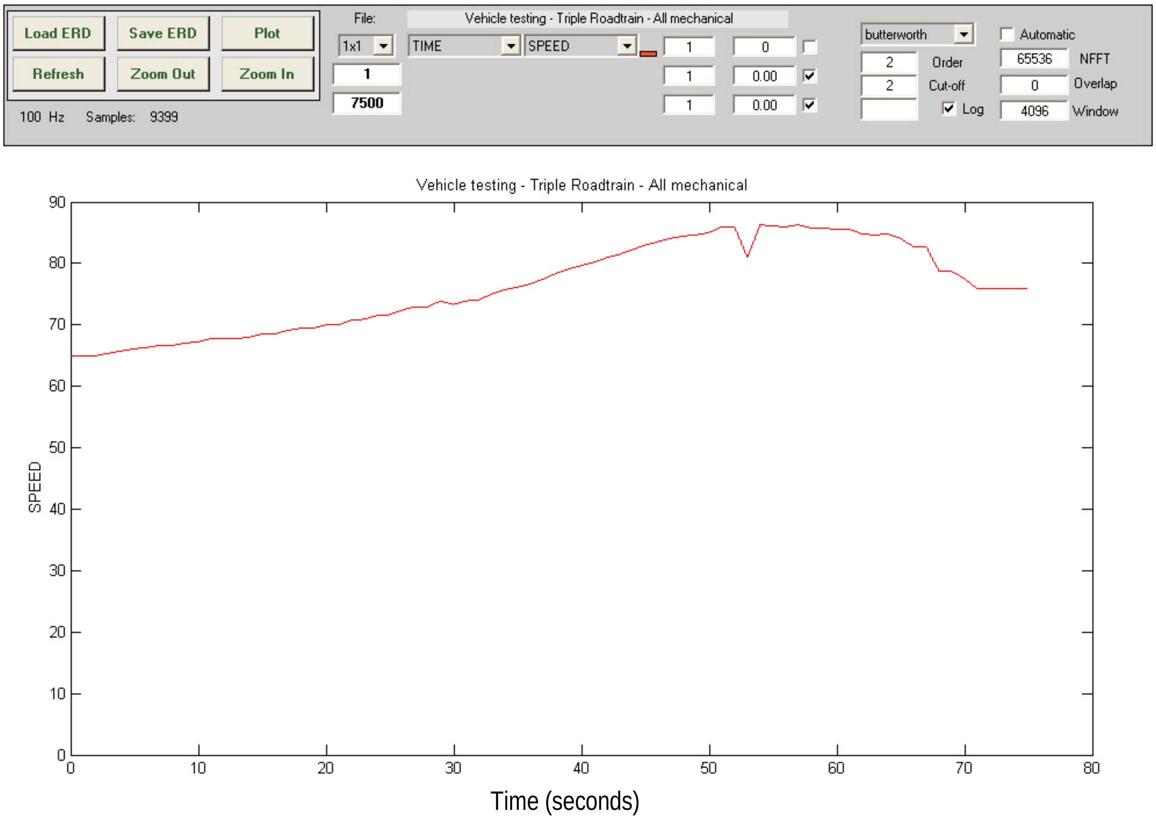

Figure 75. Vehicle 3 – 949 Lane Change - Speed

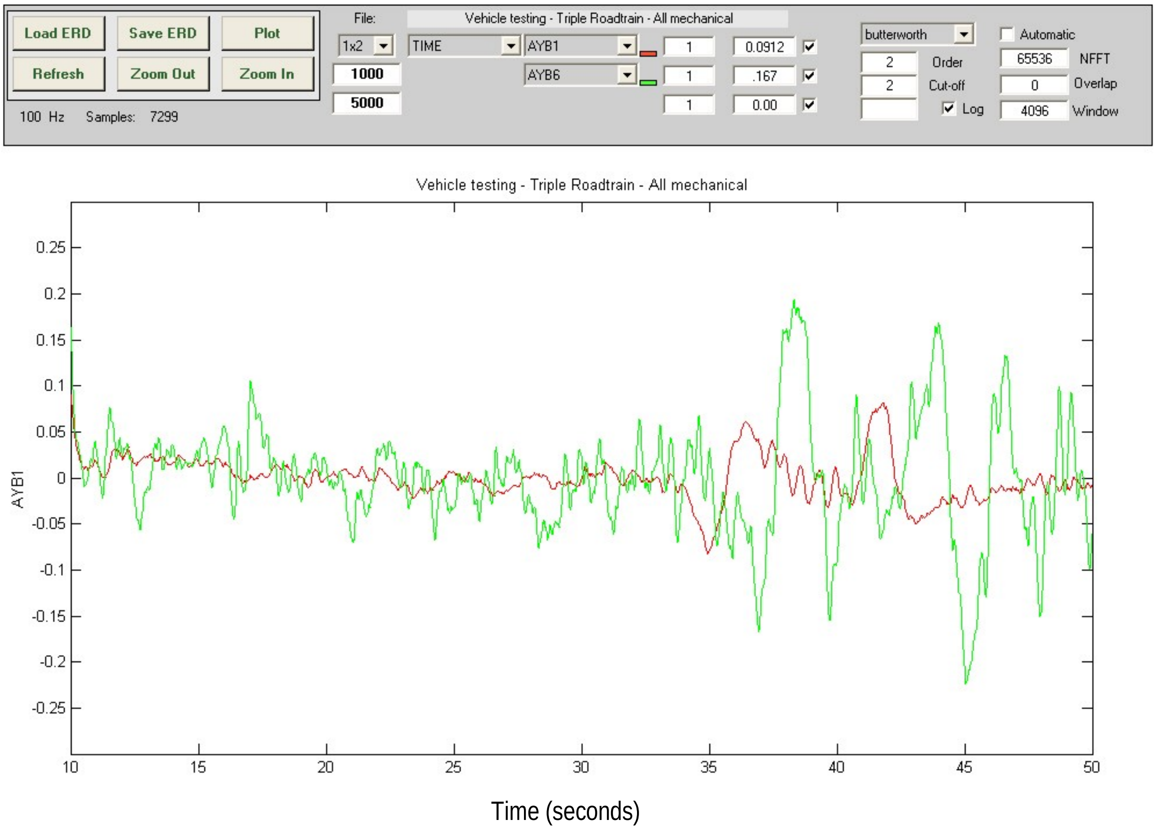

Figure 76. Vehicle 3 – 1001 Lane Change

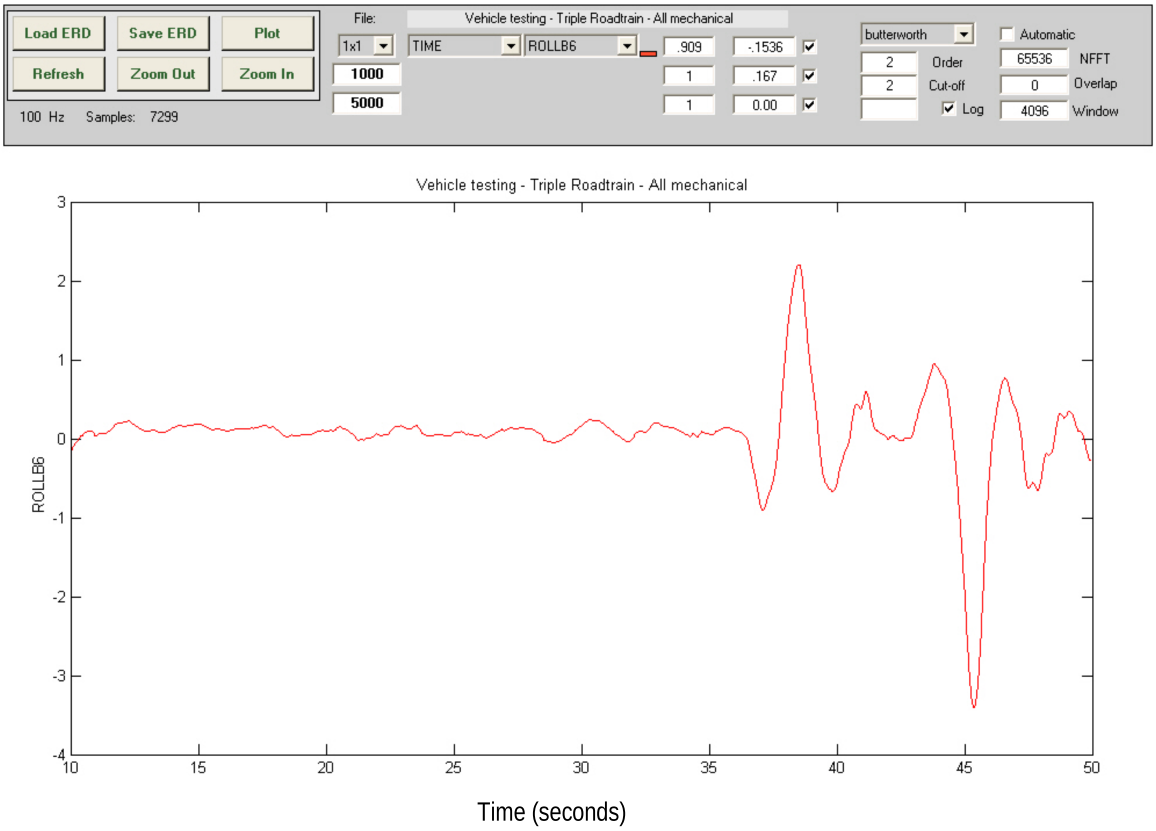

Figure 77. Vehicle 3 – 1001 Lane Change – Roll

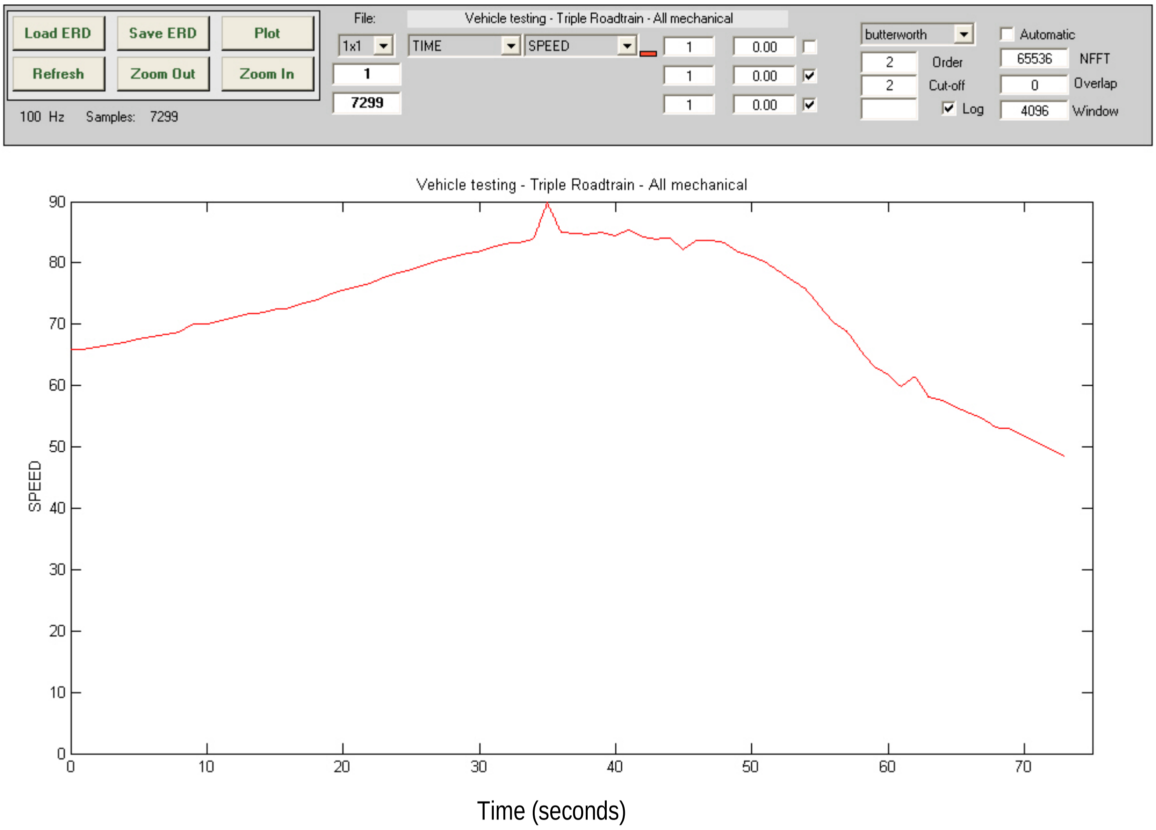

Figure 78. Vehicle 3 – 1001 Lane Change – Speed

Table 32. Data statistics – Lane change maneovre

No. File	Chan.	Gain	Offset	Min	Max				Mean	Med
1	0918Fri0904	AYB1 1.0		0.06	- 0.097 0.069 -.	0007		0.0020	.0176	
1 0918Fri0904	AYB6 1.0		0.45	- 0.160	0.589 .0	004 8	0.0001	.041		
1 091 8Fri0904	ROLLB6	1.0	- 7.865	-1.24 1	.782				.00018 0	.062 9
2 084 4Sat1004	AYB1	1.0	- 0.011	- 0.114	0.072 .0	001 5	-.0007	0.0192		
2 084 4Sat1004	AYB6	1.0	- 0.011	- 0.117	0.146 -.	0007	-.0023	0.0303		
2	0844Sat1004 ROLLB6 1.0			- 7.865	-1.06 1.568					-.0460
2 090 6Sat1004	AYB1	1.0	- 0.0125	- 0.113	0.135 -.0	0002	-.0028	0.0257		
2 090 6Sat1004	AYB6	1.0	- 0.2834	- 0.287	0.513 -.0	0025	0.0015	0.0609		
2 090 6Sat1004	ROLLB6	1.0	-7.865	-1.96	2.122				-0.0346	-.0164
2 092 7Sat1004	AYB1	1.0	- 0.0125	- 0.133	0.107 0.	0046	0.0045	0.0251		
2 092 7Sat1004	AYB6	1.0	- 0.2834	- 0.294	0.306 .0	0045	-.0012	0.0568		
2	0927Sat1004 ROLLB6		1.0	-7.865	-2.23 1.969					-0.0544
3 093 4Sun1104	AYB1	1.0	.1328	- 0.086	0.132 .0	0001	0.0006	0.0168		
3 093 4Sun1104	AYB6	1.0	.2946	- 0.172	0.294 -.0	0002	-.0029	0.0415		
3 093 4Sun1104	ROLLB6	1.0	.238	- 1.332	1.043 .0	00034	0.0157	0.1942		
3 094 9Sun1104	AYB1	1.0	.07929	- 0.061	0.079 -.0	0001	0.0002	0.0164		
3	0949Sun1104 AYB6		1.0	.1311	-0.21 0.192 .00004			-.0001	0.0453	
3 094 9Sun1104	ROLLB6	.909	-.2725	-1.83	1.782				-0.0248	0.0169
3 100 1Sun1104	ROLLB6	.909	-.1536	-3.41	2.230				.000011	0.0464
3 100 1Sun1104	AYB1	1.0	0.0912	- 0.083	0.091 .0	0001	-.0005	0.0232		
3 100 1Sun1104	AYB6	1.0	.167	- 0.224	0.1933 .	00004	-.0004	0.0612		

Table 33. Data statistics – Route testing

No.	File	Chan.	Gain	Offset	Min	Max	Mean	Med	Std
1	0703Fri0904	STEER	0.2587	-2.057	-92.20	90.89	-.00006	-.098	.967
1	0703Fri0904	STEER 450-850	0.2587	-2.057	-2.66	4.08	-0.5318	-.600	0.884
1	0703Fri0904	AYB1	1.0	0.0457	-0.20	0.17	-.00003	-0.011	0.037
1	0703Fri0904	AYB6	1.0	0.0269	-0.27	0.20	.00003	-.007	0.047
1	0703Fri0904	YAWB1	1.0	0.004	-14.26	16.31	-.0002	-.026	1.506
1	0703Fri0904	YAWB6	1.0	-1.496	-10.74	14.20	.00035	-.216	1.656
1	0703Fri0904	SPEED 450-850	1.0	0.0	13.33	89.27	61.634	62.63	19.50
1	0703Fri0904	AYB1 450-	1.0	0.0457	-0.07	0.08	0.0049	-.004	.029
1	0703Fri0904	AYB6 450-	1.0	0.0269	-0.21	0.14	-0.004	-.005	0.037
1	0703Fri0904	YAWB1 450-	1.0	0.004	-1.69	1.53	0.1127	0.034	0.437
1	0703Fri0904	YAWB6 450-	1.0	-1.496	-2.39	2.21	-0.4062	-.514	0.561
1	0735Fri0904	STEER	0.2587	-3.2453	-82.41	91.02	-.00003	-.814	12.21
2	0731Sat1004	STEER	0.2587	-0.421	-74.47	90.72	.00006	0.221	7.198
2	0731 Sat1004	STEER 300-	0.2587	-0.421	-4.84	5.22	0.1406	0.142	0.843
2	0731 Sat1004	AYB1	1.0	0.04117	-0.31	0.20	-.00001	-.009	0.039
2	0731 Sat1004	AYB6	1.0	0.0628	-0.23	1.08	.00001	-.008	0.046
2	0731 Sat1004	AYB1 300-800	1.0	0.04117	-0.11	0.12	-0.002	0102	0.031
2	0731 Sat1004	AYB6 300-800	1.0	0.0628	-0.16	0.25	-0.0018	-.008	0.038
2	0731 Sat1004	Speed	1.0	0.0	0.00	84.64	53.216	54.09	18.90
2	0731 Sat1004	Speed 300-800	1.0	0.0	33.34	83.71	61.154	60.81	13.21
2	0731 Sat1004	YAWB1	1.0	-0.0145	-15.47	18.04	-.00006	-.0376	1.578
2	0731 Sat1004	YAWB6	1.0	0.0190	-12.38	15.49	.00001	-.064	1.768
2	0759 Sat1004	STEER	0.2587	-.1008	-72.06	79.77	.00003	0.060	7.943
3	0800 Sun1104	STEER	0.1915	1.648	-111.0	80.37	-.00006	-.039	9.523
3	0800 Sun1104	STEER 500-	0.1915	1.648	-11.41	21.70	0.8094	-.021	3.952
3	0800 Sun1104	AYB1	1.0	0.03165					
3	0800 Sun1104	AYB6	1.0	0.07615					
3	0834 Sun1104	STEER	0.1915	0.01993	-83.09	107.37	.00001	-1.395	11.28
3	0834Sun1104	AYB1	1.0	0.02331	-0.188	0.42	.00001	-.025	0.074
3	0834Sun1104	AYB6	1.0	0.06795	-0.316	1.24	.00001	-.055	0.208

Table 34. Data statistics of steering input – Route testing

No.	File	Section	Gain	Offset	Min	Max	Med	Range	Std
1	703Sat10 04	Entire route	.26	-.53	-24.2	23.8	-0.00	48.0	2.06
2	731Sat10 04	Entire route	.26	-.11	-20.1	23.9	0.05	44.0	1.87
3	800Sun 1104	Entire route	.19	.32	-21.3	15.4	-0.01	36.7	1.82
1	703F ri0904	GEHB	.26	-.40	-1.1	0.8	-0.01	1.9	0.16
1	703F ri0904	Roe Hwy	.26	-.45	-0.8	1.4	-0.05	2.2	0.25
2	731Sat10 04	GEHB	.26	-.14	-0.5	0.6	-0.00	1.1	0.12
2	731Sat10 04	Roe Hwy	.26	-.18	-0.8	1.3	-0.03	2.1	0.24
3	800Sun 1104	GEHB	.1915	.94	-0.8	0.9	0.01	1.7	0.18
3	800Sun 1104	Roe Hwy	.1915	.64	-0.5	0.6	-0.01	1.1	0.19