DYNAMIC STABILITY OF DOUBLE B-DOUBLE ROAD TRAINS

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ABSTRACT

In response to concerns over the lateral road space requirements and stability of a fleet of rigid plus double B-double (R2B2) road trains operating in remote Western Australia, investigations were conducted of various options for improving the on-road performance of the vehicles. The vehicles, having a gross mass of over 150t and an overall length of 51.4m, were observed in operation to exhibit excessive swaying of the rearmost trailers. This swaying was found to increase with vehicle speed, and has been raised as being of concern by other road users. An inspection of the vehicles revealed a rearward location of the tow coupling on the rigid truck, and elevated positions of the load bins, both of which contribute to increased rearward amplification, and hence to swaying and increased road space requirements. A change to a double B-double (2B2) configuration was proposed, replacing one of the load bins on the rigid truck and the first dolly with a turntable on the rear of the truck. This removes one articulation point and the long coupling rear overhang, with a slight reduction in payload capacity. In order to quantify the effect on swaying and road space requirements of the proposed change in configuration, comprehensive whole-of-vehicle computer-based models of the two vehicle configurations were created. In simulations of a standard lane change and pulse steer manoeuvres, the 2B2 exhibited superior dynamic stability. Additional simulations were conducted, revealing that reducing the load centre-of-gravity height, increasing the trailer suspension roll stiffness, and increasing tyre cornering stiffness all would lead to further improvements in dynamic stability and road space requirements.

1. INTRODUCTION

1.1 Road Transport in Western Australia

The State of Western Australia (WA) makes up the western third of the Australian land mass (see Fig. 1). The State is rich in mineral wealth with agriculture its second major industry. As there is a limited rail network, much of the mineral material and agriculture product is transported by road, usually over long distances, from areas remote from the export ports and to a limited number of high capacity, low unit cost processing plants/facilities often located at coastal centres.

Transport of livestock from inland areas to the coastal cities for processing or live export is also by road. General freight is also hauled over long distances, for example, from Perth, WA's capital city located in the South of the State, to destinations in the far North of the State.

To enable the mining and agriculture industry to maintain its international competitiveness, the transport component of the cost of export minerals and agriculture needs to be minimised. Most of the state is very flat and dry with low traffic volumes; circumstances that are ideal for the operation of large road trains which are often used.

1.2 Main Roads Western Australia Management of Road Trains

The government authority responsible for managing Western Australia's road asset is Main Roads Western Australia (MRWA). To enable road trains to access specific parts of the road network, MRWA issues individual permits to road transport operators and it also gazettes routes. MRWA works with local government when road trains need to travel on local government roads.

The two vehicles described in this paper – a road train comprising a rigid 5-axle truck towing a double B-double trailer set, shown in Fig. 2(a) and referred to herein as an R2B2[1], and another one comprising a 5-axle prime-mover towing a double B-double trailer set, shown in Fig. 3 and referred to as a 2B2 – operate under a permit. The permit allows up to 23.5 t to be carried on tri-axle groups as opposed to the 20 t normally allowed, as the operator has loading controls in place that ensure this higher axle-load limit is not exceeded.

The vehicles are used to transport nickel concentrate and they operate on local government roads for much of their journey.

1.3 Responsibility to Community

In issuing permits and managing the use of the road network by large road trains, MRWA must ensure the vehicles are safe, and that wear and tear on the infrastructure is acceptable. Further, MRWA must also ensure nuisance and inconvenience to other road users and the community is maintained at a level that is acceptable to all stakeholders.

People in the local community expressed grave concerns with the on-road behaviour of the rigid plus double B-double combinations (R2B2). They reported that at times the rear trailer swayed violently, often well outside the traffic lane. They advised that it was of great concern and some motorists would not share the road with these vehicles.

The operator was also well aware of the concerns of both the road users and the community. In an attempt to improve the vehicle's on-road safety performance the following series of changes was made and tested:

- Replacing dampers.
- Reverting to 20 t on tri-axle groups to achieve a lower centre-of-gravity (CG) height.
- Using dollies with steel spring suspensions in place of the original air spring suspensions.
- Using lower profile semi-oscillating turntables in lieu of the ball-race type turntables.
- Using low profile tyres.
- Restricting the operating speed to 70km/h. This proved to be a partial solution to the rear-trailer swaying problem but was not acceptable to the operator being able to keep to driving hours schedules and to other road users due to the higher speed differential between the trucks and other traffic.
- Different height settings on the air spring suspensions.
- Trialing the use of a 4-axle (twin-steer tandem drive) instead of a 5-axle (twin-steer tri-axle drive) hauling unit. This meant that the towing hitch rear overhang was reduced. An improvement in performance was evident from this step, which suggested overhang of the towing hitch on the hauling unit was a significant causal factor for poor dynamic performance. The axle-group loads of the road train with the 4-axle rigid hauling unit was raised to 23.5 t on tri-axle groups, and this showed no degradation in dynamic performance. This led MRWA to believe that for this configuration of road train coupling rear overhang was an important factor having a significant influence on dynamic performance. Therefore, conversion to a prime mover hauling unit, which would completely eliminate coupling rear overhang on the hauling unit (and one point of articulation), was believed to be a potential solution.

Another major factor found to affect dynamic performance is road unevenness (Prem, Ramsay and Fletcher, 2000). Some sections of the road used by these trucks had been widened by about one metre. This widening, which was done at the edge of the existing pavement, sometimes had greater unevenness than the pavement in the centre of the road. The path of the wheels near the edge of the seal on these widened uneven sections of the pavement translated to dynamic disturbances in the road trains' lateral motion.

The concerns of the community and other road users led to MRWA commissioning RTDynamics to investigate the performance of two road trains. MRWA proposed that the vehicle configuration in use be changed, from a rigid truck towing a double B-double (R2B2) to a prime mover and double B-double (2B2), to improve on-road performance.

[1] The nomenclature system for describing heavy vehicle configurations is fully described in Ramsay, Prem and Peters (2000).

The aims of the investigation performed by RTDynamics were to verify the benefits of the proposed configuration change, and through a parametric study quantify the influence on performance of key mechanical properties. The study was designed to both use and to confirm the main observations described above[2].

1.4 Performance-Based Standards (PBS) Approach

Austroads[3] and the National Road Transport Commission (NRTC) have developed a range of performance-based standards (PBS) for evaluating the safety and infrastructure related performance of heavy vehicles. The performance standards have been tested against a wide range of vehicles from the Australian heavy vehicle fleet (Prem et al, 2002). MRWA decided to adopt a PBS approach to the assessment of the performance of the road trains' considered. This approach enables the dynamic performance of heavy vehicle combinations to be quantified and the performance of different vehicle combinations to be objectively compared.

2. OBSERVATIONS

2.1 On-Road

As part of the investigation carried out for MRWA by RTDynamics, the vehicles were observed in operation on the Geraldton to Mt Magnet Road. The road was found to be in generally adequate condition, with roadwork in progress to address some previously identified deficiencies. Several laden vehicles were followed and observed as they headed towards Geraldton. Although some swaying was evident, the lane width appeared to be sufficient to ensure that the vehicle did not encroach into oncoming traffic lanes or drop off the road shoulder (see Fig. 2).

2.2 Roadside Inspection

The rigid plus double B-double road train, or R2B2, shown in Fig. 3(a) was inspected near Geraldton. It was noted that the tow coupling on the rigid truck prime mover was located some distance rearward of the drive group centre, as can be seen in Fig. 3(b). Combined with an additional point of articulation (the front dolly), this would contribute to increased rearward amplification, and swaying of the trailers (Ervin et al, 1986; Austroads, 2000).

Additionally, it was noted that the load bins (kibbles) were located high on the trailer chassis rails (see Fig. 3(c)). A raised CG of the trailers leads to a lower static rollover threshold and decreased dynamic stability (Ervin et al, 1986; Austroads, 2000).

It was proposed by MRWA to change to a double B-double configuration (2B2) by removing the front tri-axle dolly and coupling the front trailer directly onto the prime mover, as shown in Fig. 4. One less kibble would be able to be carried by the new configuration; however, while it was known there would be an improvement in the dynamic stability it was not known how much would result from this change.

3. COMPUTER MODELS AND SIMULATIONS

Computer-based models were created of the R2B2 configuration and of the proposed revised configuration (2B2), and a range of simulations were performed based on a selection of the safety-related performance measures developed by Austroads and the NRTC (Prem et al, 2002). These were used to quantify the effects of the proposed changes on dynamic stability and road space requirements, and also to give indications of the effects on performance of varying several key design parameters.

The models were created using the ADAMS multi-body dynamics simulation software (Mechanical Dynamics Inc., 2002), together with the truck modelling toolbox developed by RTDynamics (RTDynamics, 2002a; 2002b). Full three-dimensional, dynamic models of the vehicles were created, including controllers for speed, traction control and steering.

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2 Further observations of the behaviour of these road trains showed that on long downgrades a swaying of the rear trailers developed. This behaviour may be due to units of the combination being in longitudinal compression, which would produce a destabilising yaw moment on each unit in the combination. When the prime mover reverted to pulling the trailers uphill the swaying abated. This behaviour was not investigated as part of the work carried out by RTDynamics described in this paper.

3 Austroads is the association of Australian and New Zealand road transport and traffic authorities.

Detailed non-linear air suspension models were used on the drive, dolly and trailer axle groups, and a non-linear multi-leaf steel spring suspension model based on Fancher et al. (1980) was used for the steer axle. Validated tyres models were based on those developed by Gim (1988).

Fig. 5(a) shows the computer model of the R2B2 that is depicted in Figs 3(a) to 3(c). Using the translucency features within ADAMS, some of the detail of the hauling unit is revealed in Fig. 5(b), showing the location of the drawbar hitch, drive group suspension, drive train, engine and gearbox, fuel tanks, steer axle suspension and steering arrangement.

The two road train models were simulated in the SAE lane change manoeuvre (Society of Automotive Engineers, 1993), in which a single lane change of width 1.46 m is executed at a speed of 88 km/h over a distance of 61 m. A second simulation was performed, in which a steer angle pulse is applied at the road wheel over a 0.1 s period. Test speed for the pulse steer manoeuvre is 100km/h.

The responses of the computer models were compared to each other and to those of a reference vehicle model, representing a full-size, commonly used, triple road train with a low CG hauling similar mining product to the two vehicles studied. The triple road train is referred to in this paper as TRIPLE, as shown in Fig. 6.

The dynamic responses of all three models were compared using three of the performance measures developed by Austroads/NRTC (Prem et al, 2002).

4. PERFORMANCE MEASURES

The following three performance measures from those proposed by Austroads/NRTC (Prem at al, 2002) were selected to characterise the dynamic stability of the road trains considered in this paper: rearward amplification, high-speed transient offtracking and yaw damping coefficient. These are briefly described in the following sections; a full description is given in Prem et al (2001) and Prem et al (2002).

4.1 Rearward Amplification

Rearward Amplification (RA) is a measure of the tendency of the trailing unit(s) of a multi-articulated vehicle to amplify any lateral acceleration experienced at the hauling unit. The performance requirement for RA set by Austroads and the NRTC, which assumes the SAE lane change is representative of a typical evasive manoeuvre, is defined in terms of the rollover stability of the critical, rearmost roll-coupled unit, as follows:

$$RA \quad 5.7SRT_{rrcu} \tag{1}$$

where:

RA = rearward amplification measured in accord with recommended practice SAE J2179 or ISO 14791 (-)

SRT_{rrcu} = static rollover threshold of the rearmost roll-coupled unit (g)

For a vehicle with a static rollover threshold of 0.35g, Eqn (1) sets the performance level for RA at 2.0, a performance level that is based on research carried out in the USA (Fancher et al, 1989; Winkler et al, 1992)[4]. Further, according to Eqn (1), larger values of RA are deemed to be acceptable only if accompanied by a commensurate increase in the rollover stability of the rearmost roll-coupled unit(s). Both SAE J2179 and ISO 14791 are accepted methods of testing, being well established and proven procedures that are fully documented (Society of Automotive Engineers, 1993; International Organisation for Standardisation, 2000). Further details on development of the revised performance level for RA can be found in Prem et al (2002).

In practical terms, a threshold value of 2.0 for RA means that the lateral (sideways) acceleration at the CG of the rearmost unit in the combination should not exceed twice the lateral acceleration at the centre of the steer axle of the hauling unit. In the SAE lane change manoeuvre the steer axle lateral acceleration has a peak value of 0.15g. Therefore, for the example cited, an RA that is less than 2.0 would be considered to be acceptable.

[4] During development of the Austroads/NRTC performance standards a set performance level of 2.0 for RA was also proposed (see Prem et al, 2001). However, the form described by Eqn (1) is preferred because it directly links the performance requirement to rollover stability, discussed fully in Prem et al (2002).

4.2 High Speed Transient Offtracking

High Speed Transient Offtracking (HSTO) measures how far the rear of the combination vehicle tracks outside the path taken by the hauling unit during the SAE lane change manoeuvre. The performance standard for HSTO requires that the centre of the rear of the last trailer of the combination vehicle remain within 800 mm of the path taken by the centre of the steer axle (Prem et al, 2001; Prem et al, 2002).

4.3 Yaw Damping Coefficient

Yaw Damping Coefficient (YDC) quantifies how quickly oscillations of the last trailer take to reduce in amplitude, ie. settle, after the application of a short duration steer input at the hauling unit. Vehicles that take a long time to settle increase the driver's workload and represent a higher safety risk to other road users. Under the Austroads/NRTC performance standards (Prem et al, 2002) the yaw-damping coefficient is required not to be less than 0.15 for yaw damping to be considered acceptable.

5. RESULTS

The results for the three vehicles are presented in summary form in Table 1. This shows that relative to the specified performance levels considered, the performance of the 2B2 was superior to the R2B2.

The greatest change in percentage terms was seen in the high-speed transient offtracking, which decreased from 1.28m to 0.59m, a reduction of 54%. The results for the 2B2 all met the Austroads/NRTC performance standards, with the exception of YDC, falling short by 7.3% of the performance level specified.

Table 1 also shows that both the previous configuration (R2B2) and the TRIPLE meet the RA performance standards but they do not meet the HSTO requirement. However, the performance of the TRIPLE, in terms of RA and HSTO, lies between the R2B2 and the 2B2.

6. PARAMETRIC STUDY

As a consequence of the 2B2 configuration meeting two of the three performance standards considered in this study, and almost meeting the third, a series of further simulations were conducted to determine if additional performance improvements could be achieved by making changes to some of the vehicle's mechanical properties. These changes may need to be considered if the vehicle were to operate under a concessional loading scheme where the tri-axle group loads would be increased from 20.0 t to 23.5 t. The following four scenarios were examined:

1. Reduce CG height by 100mm, such as by lowering the position of the kibbles (see Fig. 3(c)).
2. Increase the roll stiffness of the trailer and dolly suspensions by 20%.
3. Increase the tyre cornering stiffness by 20%; as could be achieved by using low profile tyres, or as could occur with normal tyre wear[5].
4. All of the above three combined.

Table 2 presents the results of making these changes on the three performance measures considered. The greatest improvement in RA and HSTO, which would be reflected in road space requirements, was found to occur in changing to tyres that have greater cornering stiffness. It is possible to realise this by moving to low profile tyres, or, mindful of all the possible safety considerations and the associated implications, by using tyres with less tread on the rear trailers and saving the tyres with more tread for the front trailers. Increased cornering stiffness also gave the greatest increase in YDC, which would meet the performance standard, and cause sway oscillations of the trailer to both decrease more rapidly and execute fewer oscillations.

The influence of lowering trailer CG by 100mm (a reduction in CG height of about 6%) and increasing suspension roll stiffness is less than that of increasing tyre cornering-stiffness, but is still significant, emphasising the need to both design for as low a CG as practical while also using suspensions with the highest practical roll stiffness.

Table 2 shows the improvement toward achieving the specified performance levels is substantial when all three changes are introduced simultaneously, and ranges from about 20% for RA, in excess of 45% for HSTO, and 51%

[5] It is useful to note that with wear the cornering-stiffness of tyres can increase by up to about 20% (Fancher et al, 1986).

for YDC. It is also useful to note that for all three performance measures (RA, HSTO and YDC), the improvement when all three design changes are introduced simultaneously is greater than the improvement due to each change made independently, emphasising the interactive nature of the parameters considered and their influence on vehicle dynamics.

The changes identified, if practical and introduced concurrently, are predicted by the modelling to produce significant improvements in the safety-related on-road performance of the 2B2 configuration by meeting the three performance standards considered.

7. CONCLUSIONS

7.1 Summary of Findings from Computer-Based Modelling

The computer-based simulations have suggested that the double B-double (2B2) configuration would be expected to have a better dynamic performance than the rigid plus double B-double (R2B2) configuration. This improvement should be evident in less swaying of the trailers and in reduced road space requirement. Much of this improvement could be attributed to the elimination of the coupling rear overhang and one articulation point.

Further improvements in dynamic stability and road space requirements can be realised by lowering the load height and hence the CG, by increasing suspension roll stiffness, and by using tyres with greater cornering stiffness.

There is a range of other performance enhancing design changes that could be made to road trains, which could be explored and their effect quantified cost effectively through computer-based modelling as demonstrated in this paper.

7.2 Feedback on Operation following Conversion of Hauling Units

The initial findings of this investigation were published in June of 2001 (Ramsay and Prem, 2001). All hauling units have since been converted from rigid trucks to prime movers, and MRWA has now been receiving positive feedback on the operation of the revised configuration. This is in line with the improved dynamic performance predicted by the computer modelling.

Given this link between observed on-road performance and simulated behaviour, MRWA will continue using the PBS approach and whole-of-vehicle computer-based modelling for assessing the performance of large heavy vehicles in the future. The study and subsequent changes to the hauling units showed that the PBS approach is an effective way to assess heavy vehicle performance without the need to instrument and test actual vehicles.

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REFERENCES

AUSTROADS (2000). *Performance Measures for Evaluating Heavy Vehicles in Safety Related Manoeuvres.* Publication AP-147/00. Austroads: Sydney, 2000.

FANCHER, P.S., ERVIN, R.D., MacADAM, C.C. and WINKLER, C.B. (1980). *Measurement and Representation of the Mechanical Properties of Truck Leaf Springs.* SAE Paper No. 800905. Society of Automotive Engineers, Inc.: Warrendale, PA, United States.

FANCHER, P.S., ERVIN, R.D., WINKLER, C.B. and GILLESPIE, T.D. (1986). *A Factbook of the Mechanical Properties of the Components for Single-Unit and Articulated Heavy Trucks.* Report No. UMTRI-86-12, University of Michigan Transportation Research Institute: Ann Arbor, MI, USA,1986.

FANCHER, P.S., MATHEW, A., CAMPBELL, K., BLOWER, D. and WINKLER, C.B. (1989) *Turner Truck Handling and Stability Properties Affecting Safety: Final Report - Volume 1 - Technical Report,* Report No. UMTRI-89-11-1, 206p. University of Michigan Transportation Research Institute, Ann Arbor.

GIM G. (1988) Vehicle Dynamics Simulation with a Comprehensive Model for Pneumatic Tires. Ph.D. Thesis. University of Arizona. (Department of Aerospace and Mechanical Engineering: Tucson, AZ, USA).

INTERNATIONAL STANDARDS ORGANISATION (2000). *Road Vehicles – Heavy Commercial Vehicle Combinations and Articulated Buses - Lateral Stability Test Methods.* International Standard ISO 14791: 2000. International Organisation for Standardisation: Geneva, Switzerland.

MECHANICAL DYNAMICS (2002) *Internet Site - http://www.adams.com.* Mechanical Dynamics: Inc., Ann Arbor, MI, United States, 2002.

PREM, H., RAMSAY, E.D. and FLETCHER, C.A. (2000). Lane Width Requirements for Heavy Vehicles. *Proceedings of the 6th International Symposium on Heavy Vehicle Weights and Dimensions*, June 18-22, pp 459-470. Saskatchewan Highways and Transportation: Regina, Saskatoon, Canada.

PREM, H., RAMSAY, E.D., McLEAN, J.R., PEARSON, R.A., WOODROOFFE, J.H.F. and DePONT, J.J. (2001). *Definition of Potential Performance Measures and Initial Standards*". Discussion Paper. Prepared for National Road Transport Commission: Melbourne, Vic.

PREM, H., DePONT, J.J. PEARSON, R.A. and McLEAN, J.R. (2002). *Performance Characteristics of the Australian Heavy Vehicle Fleet.* Prepared for National Road Transport Commission: Melbourne, Vic.

RAMSAY, E.D., PREM, H. and PETERS, R.J. (2000). An International Heavy Vehicle Nomenclature System. *Proceedings of the 6th International Symposium on Heavy Vehicle Weights and Dimensions*, June 18-22, pp 459-470. Saskatchewan Highways and Transportation: Regina, Saskatoon, Canada.

RAMSAY, E.D. and PREM, H. (2001). Dynamic Stability of Double B-Double Road Trains (Preliminary). *Regional Road Train Summits, Kalgoorlie and Geraldton, Western Australia, June 2001.*

RTDYNAMICS (2002a). *RTDynamics' ADAMS/Truck Toolbox – User Manual.* RTDynamics Internal Report – ADAMS/Truck Toolbox UM - V1.1: Bulleen, Vic. (Confidential: restricted circulation.)

RTDYNAMICS (2002b). *RTDynamics' ADAMS/Truck Toolbox – Reference Manual.* RTDynamics Internal Report – ADAMS/Truck Toolbox RM - V1.1: Bulleen, Vic. (Confidential: restricted circulation.)

SOCIETY OF AUTOMOTIVE ENGINEERS (1993). *A Test for Evaluating the Rearward Amplification of Multi-Articulated Vehicles.* SAE Recommended Practice J2179. Society of Automotive Engineers: Warrendale, PA, United States, 1993.

WINKLER, C.B., FANCHER, P.S., BAREKET, Z., BOGARD, S., JOHNSON, G., KARAMIHAS, S. and MINK, C. (1992). *Heavy Vehicle Size and Weight – Test Procedures for Minimum Safety Performance Standards.* Report No. UMTRI-92-13. University of Michigan Transportation Research Institute, Ann Arbor, Michigan, USA.

TABLES & FIGURES

Table 1 – Computer Simulation Results

Performance Measure (units)	R2B2	2B2	2B2 *cf* R2B2	TRIPLE	Performance Level
Rearward Amplification (-)	2.72 *(2.74)*	1.92 *(2.74)*	-29%	2.11 *(2.45)*	$\leq 5.7SRT_{rrcu}$ *(Performance Level)*
High Speed Transient Offtracking (m)	1.28	0.59	-54%	0.91	≤ 0.80
Yaw Damping Coefficient (-)	0.101	0.139	+38%	0.116	≥ 0.150

Table 2 – Results of Parametric Study for the 2B2

Performance Measure (units)	Baseline	Lower CG	Increase Susp'n Roll Stiffness	Increase Tyre Cornering Stiffness	All
Rearward Amplification (-)	1.92	1.89	1.86	1.63	1.51
High Speed Transient Offtracking (m)	0.59	0.55	0.56	0.37	0.32
Yaw Damping Coefficient (-)	0.139	0.144	0.143	0.192	0.210

Fig. 1 The roads network in Western Australia (from http://www.mainroads.wa.gov.au).

Fig. 2 Typical area of concern over road space requirement of road trains.

Fig. 3(a) Rigid plus double B-double (R2B2) road train inspected near Geraldton.

Fig. 3(b) Side view of rigid truck (hauling unit) showing the coupling rear overhang dimension.

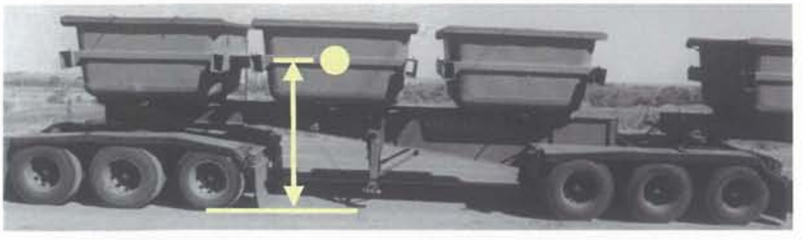

Fig. 3(c) Side view of trailer showing approximate location kibble CG.

Fig. 4 Proposed double B-double (2B2) road train configuration.

Fig. 5(a) RTDynamics computer-based model of the R2B2 shown in Figs 3(a) to 3(c).

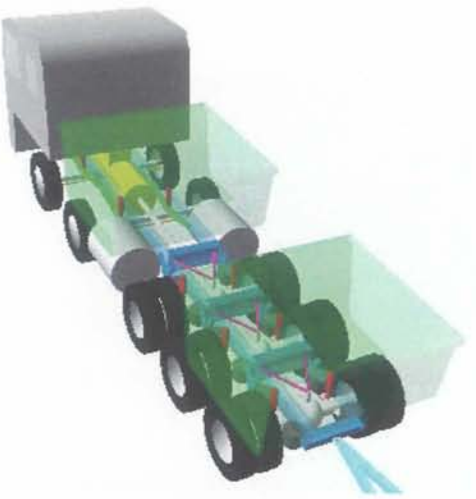

Fig. 5(b) Computer-based model of R2B2, hauling unit detail shown.

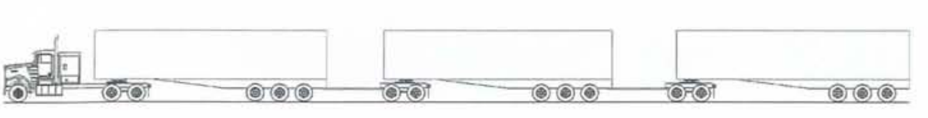

Fig. 6 Low CG, reference triple road train (TRIPLE); 12S3-2S3-2S3.