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MECHANICAL DESIGN OPTIMISATION OF A SUGARCANE HAULAGE VEHICLE

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Abstract

The South African sugar industry transports in excess of 20 million tons of sugarcane per annum, equating to approximately 800 000 road consignments. This entails substantial expenditure on vehicle capital and operational costs. Weight reduction of a transport vehicle body significantly reduces transport costs. In this study, the design of a sugarcane truck is optimised. The basic starting parameters were acquired from various truck trailers in operation in South Africa, and were optimised with respect to mass, through various optimisation analyses. The objective was to decrease the overall tare mass of the vehicle while improving its structural integrity. This will result in an increase in payload, thereby reducing the transportation cost of raw sugarcane.

Keywords: sugarcane, design optimisation, truck-trailer, tare mass, sugarcane transport, transportations cost, finite element analysis

Introduction

Research into cost analysis on transportation and other relevant costs of sugarcane production reveals that transportation has become a significant factor affecting the production costs of sugar (Chetthamrongchai *et al.,* 2001). The South African sugar industry transports in excess of 20 million tons of raw sugarcane per annum, resulting in approximately 800 000 road consignments. This entails substantial expenditure on vehicle capital and operational costs.

The South African Sugarcane Research Institute (SASRI) has implemented a full-scale investigation into the transport of raw sugarcane in an attempt to reduce the cost. The project includes many aspects of the entire transportation system, including logistics optimisation through the use of satellite vehicle tracking and scheduling, automatic on-board weighing, central tyre inflation systems, performance based standards and tare mass reduction through design optimisation, which is the main focus of this research.

Tare mass reduction in a vehicle body can substantially reduce the costs associated with transport (Lathen, 1998; Lan, 2004). Fuel economy alone has been shown to increase in the range of 0.034 to 0.050 km/litre/1000 kg reduction in tare mass (Taylor, 1999; Ang-Olson and Schroeer, 2003). Related industries (e.g. the South African timber industry) have achieved large reductions in transportation costs through decreasing the tare mass of haulage vehicles.

To investigate the effect of tare mass reduction on the cost of transportation in this particular case, a simulation was carried out using HTM TransSolve, a commercial logistics software package, applied to various transport and logistics-related calculations (Anon, 2006a). A simple simulation was used, where a haulage vehicle collected cane from a farm and delivered it to a mill 16.2 kilometres away. The fixed costs, such as licence fees and overheads, are constants and the simulation used a standard trailer loaded to legal capacity, and a trailer with a tare mass reduced by 8.54% and loaded to legal capacity. The results showed that the total cost of transportation was reduced from R19.67 to R18.53/ton, or a saving of 5.8%, which is substantial when the volume of cane transportation is considered. This figure is an indication of the possible cost reduction that can be achieved, as factors such as distance, cane density, vehicle finance and offloading time all affect the overall cost of transportation.

The aim of this project was to investigate the current status of vehicles utilised for sugarcane transportation, and to optimise and analyse the selected design using finite element analysis (FEA). The finite element method has become an important tool for analysing vehicle structures, and has proven to be extremely valuable to the heavy vehicle industry (Harris and Naworocki, 1984). FEA has been used in various design aspects of heavy vehicles by Karaoglu and Kuraly (2002) and Hoberg (2002), and to successfully reduce the tare mass of heavy vehicles (Lan *et al.,* 2004; Poh *et al.,* 1999), with reported weight savings ranging from 11 to 25%.

Initial vehicle selection

There are many types of vehicles currently being used in the transportation of sugarcane in South Africa. These include simple agricultural tractors with trailers, semi tri-axle trailers (tridems), tandem/tandem interlink semi-trailers and rigid drawbar vehicles. The most common configurations are shown in Figures 1, 2 and 3.

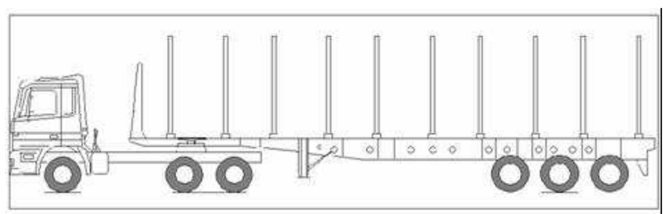

Figure 1. Typical tri-axle (tridem) configuration.

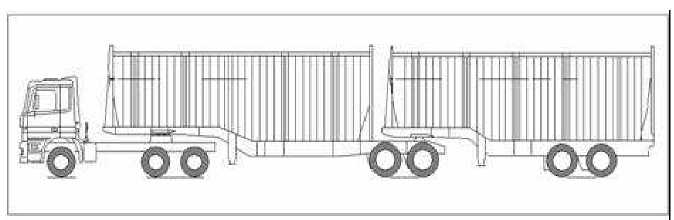

Figure 2. Typical tandem/tandem interlink configuration.

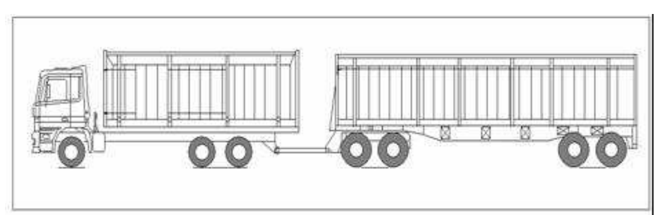

Figure 3. Typical rigid drawbar configuration.

Ten vehicles from various commercial manufacturers currently in use in South Africa were analysed to determine the mass of various components and the maximum payload. The results of this analysis are summarised in Table 1. The payload index is defined as the maximum payload divided by the tare mass of the vehicle, and is used as a rough first measure of transport efficiency.

Table 1. Vehicle mass analysis.

Truck	Tare (kg)	Payload (kg)	Payload Index	Type
1	19 930	38 870	1.95	Rigid drawbar
2	22 786	33 214	1.46	Tandem/tandem I-link
3	23 160	32 840	1.42	Tandem/tandem I-link
4	17 842	40 000	2.24	Tandem/tandem I-link (timber)
5	18 388	30 170	1.64	Tridem spiller
6	22 119	33 881	1.53	Tandem/tandem I-link
7	19 740	36 260	1.84	Rigid drawbar
8	12 380	28 000	2.26	Tridem (timber)
9	19 954	36 046	1.81	Tandem/tandem I-Link
10	23 575	32 500	1.38	Tandem/tandem I-Link
Avg	19 987.4	34 178.1	1.71	

A single tri-axle trailer (tridem) was ruled out as a possibility because, although they can be effective for short haulage distances, they generally cannot haul the same quantity of cane, and they are not as effective for medium to long distances as tandem/tandem interlink and rigid drawbar vehicles. Two timber haulage vehicles were included in the analysis for comparison. These generally tend to have a higher payload index, due to the nature of the cargo. Timber vehicles require only light retaining bolsters on the sides of the chassis to hold the cargo, whereas sugarcane vehicles need to be enclosed to retain the loose sticks. From Table 1, it can be seen that a rigid drawbar can transport a larger quantity of cane than a tandem/tandem interlink. The harvesting season lasts for approximately 36 weeks of the year, this would enable the prime mover of a tandem/tandem semi-trailer to be used for other goods during the rest of the year, and the trailer is easily adaptable to accommodate other products. In addition to this, rigid drawbar vehicles have been known to be unstable. This resulted in a tandem/tandem semi-trailer, as in Figure 2, forming the basis of the design.

It was noticed that during the offloading procedure the trailers that had a bolster structure appeared easier to offload and needed less force to lift the spiller bar than trailers that had a frame-type structure.

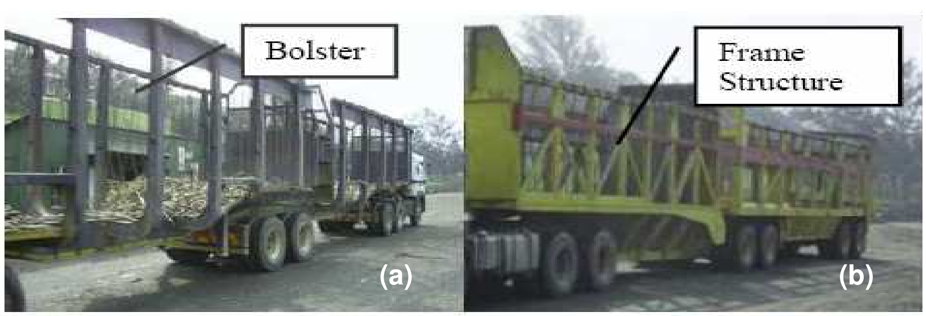

Figure 4 (a) bolster-type trailer, and (b) frame-type trailer.

Figure 4a shows that the bolster-type trailer has no horizontal or diagonal cross-members. While offloading various frame-type trailers (Figure 4b), cane was seen to get stuck in the framework, thus increasing the force required to spill the cane. The geometric shape of the bolsters also influenced the offloading process. The curved profile ensured that the cane slipped out more easily than it would have from a sharp right-angle. The fact that there is minimal area in contact with the cane, coupled with the lack of horizontal and diagonal cross-members, indicated that a bolster-type structure should be much easier to unload, with less stress on the unloading equipment and on the trailer itself.

Many factors influenced the amount of force required to spill the cane. These include whether the cane was harvested burnt or green, the manner in which the cane was loaded into the trailer and the size of the cane, in addition to the geometry of the trailer.

If a number of different readings of the forces required to spill a trailer are taken from various frame and bolster-type trailers with varied cane conditions, it is hypothesised that the averages will show that the forces required to spill a bolster-type trailer are less than those required to spill a frame-type trailer.

To verify this, readings were taken from the two load cells which are located on the unloading structure. The load cells were calibrated on a regular basis using large plastic containers filled with water and the cells indicated the forces acting on the spiller bar during the offloading process. Readings were taken for both the front and back trailers, and from each of the load cells. The six readings each taken from the front and back load cells on the two types of trailers are summarised in Table 2.

Table 2. Load cell readings for various bolster-type and frame-type trailers.

Trailer type	Bolster		Frame	
Trailer	Front (kN)	Back (kN)	Front (kN)	Back (kN)
Load cell readings	441.45	588.60	686.70	892.71
	480.69	451.26	804.42	794.61
	510.12	618.03	480.69	588.60
	382.59	500.31	794.61	696.51
	421.83	618.03	716.13	618.03
	510.12	519.93	588.60	716.13
Mean	457.80	549.36	678.52	717.76

The average readings for the front and back trailers are notably higher for the frame-type than for the bolster-type trailers. The readings for each individual trailer differ significantly, with an average variance of 14.62%. The average differences between the readings for the bolster-type and frame-type trailers are 32.53 and 23.46% for the front and back trailers, respectively. Despite the relatively high variance, the average figures confirm the previous hypothesis that the bolster-type trailers require less force exerted on the spiller bar than the frame-type trailers.

Chassis optimisation

The chassis is optimised using a simple model to determine the initial parameters. The distance between the supports of the front trailer is minimised subject to constraints which include payload, road regulation and swing clearance. A typical interlink configuration can be represented as a model composed of various lengths (see Figure 5). The front trailer is suspended by the fifth-wheel on the prime mover and the suspension assembly attached to the rear of the trailer. The second trailer is supported by a fifth-wheel mounted on the back of the front trailer, and the second suspension assembly.

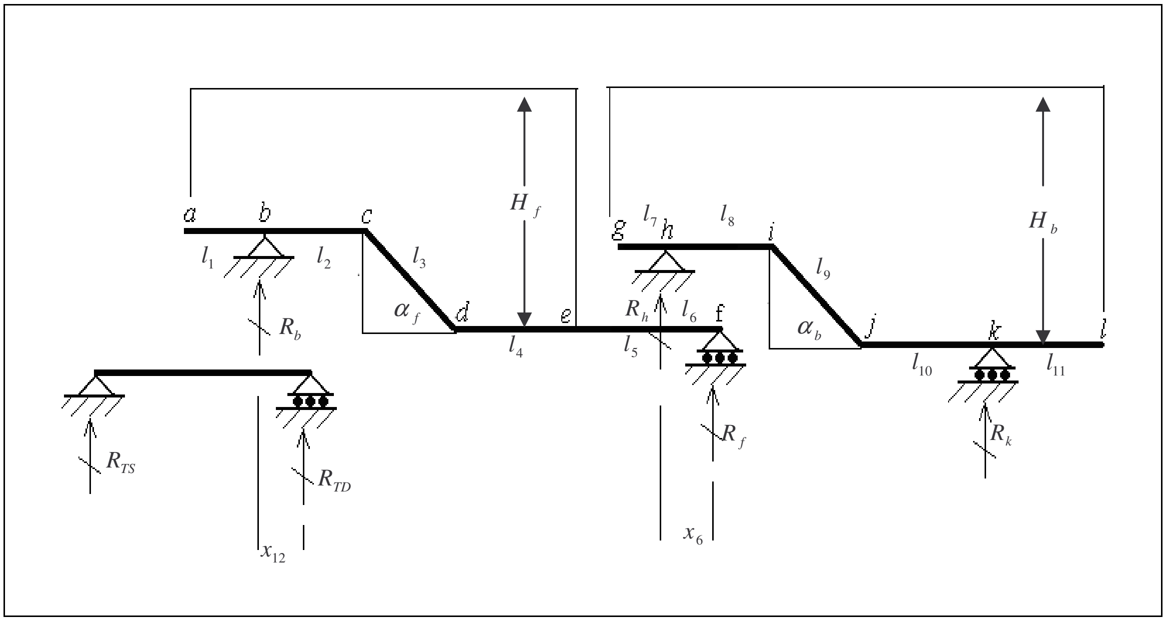

Figure 5. Model of an interlink.

The principal result of the optimised lengths was a reduction in the bending moment of the front trailer, which was reduced from 371.3 to 259.8 kNm, or a 30.04% decrease. This resulted in a decrease in the required section modulus of the main chassis beams and a reduction in the overall tare mass of the vehicle, while still meeting payload requirements.

The chassis design was also extensively analysed and reviewed using a FEA software package. The finite element method has frequently been used in the design and analysis of various components and structures in heavy vehicles, and has become an important tool for heavy vehicle designers (Harris and Naworocki, 1984). Examples of finite element analysis in the heavy vehicle industry can be found in Karita *et al*. (2003), Maasdam (1999), Clarke (2005), Anon (2005a), Anon (2006b), Sharp *et al.* (2000), Johansson and Gustavsson (2000) and Anon (2007). The finite element software that was used to analyse the vehicle structure and components is Pro/Mechanica. The software is part of the Pro/Engineer package developed by Parametric Technology Corporation. The structural and thermal simulation package (pro/Mechanica) is a multi-discipline CAE (computer-aided engineering) tool that enables the multi-physical behaviour of a model to be simulated (Anon, 2005b).

A view of the front chassis beam model is shown in Figure 6. The flanges are modelled with 1355 solid tetrahedral elements, and the web is modelled with 35 tri and 49 quad shell elements.

The beam is constrained through 10 spring elements and four points. Measures of principal and Von Mises stresses are created on the web and flanges. The back chassis beam is modelled in the same way, with 1525 solid tetrahedral, 54 tri shell and 83 quad shell elements.

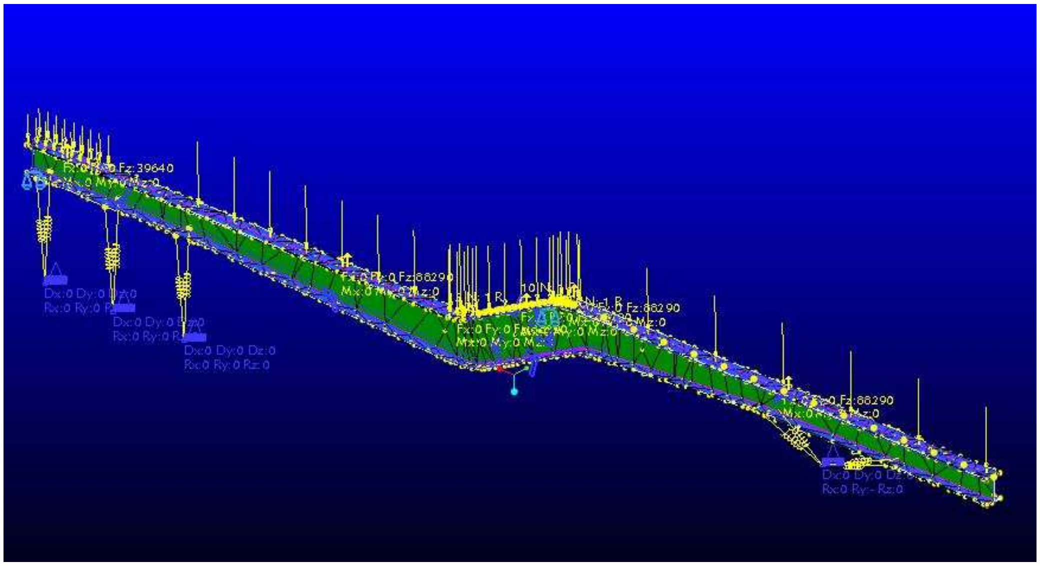

Figure 6. Simulated model of the front chassis beam.

Results

Static, accelerating and decelerating loads were investigated in this study. A dynamic design factor (DDF) of 2.75 was used for the static load. A typical result is shown in Figure 7. The Von Mises stress was highest at the points where the fifth-wheel spring constraints connected to the model. The high stress was the result of singular stress concentrations at the corners where the spring elements linked to the fifth-wheel plate, and was a fictitious critical region induced by the applied boundary conditions. This highly stressed zone was localised and did not affect the overall structure.

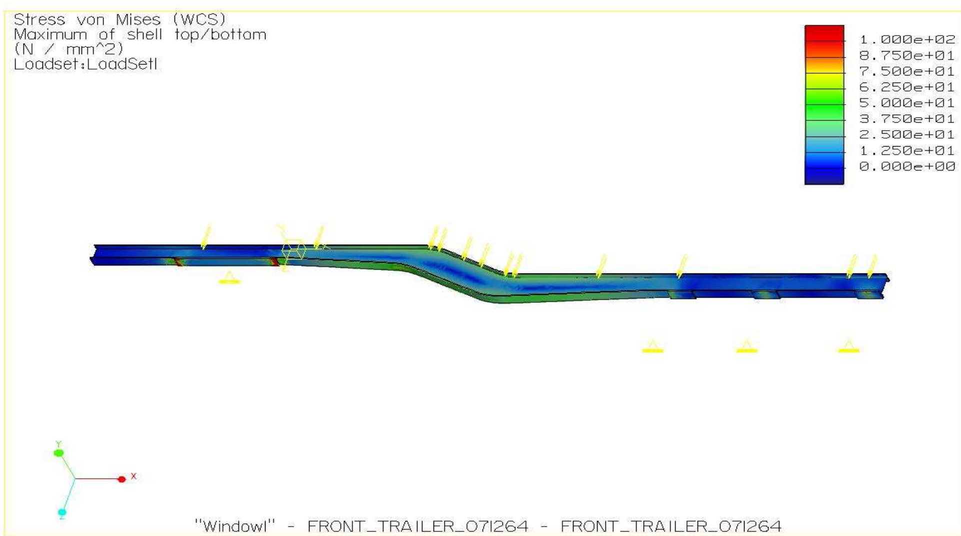

Figure 7. Fringe plot of Von Mises stress for front trailer under normal loading.

For static loading, (Figure 7), the highest stress occurred in the flanges at the middle section of the chassis beam, as expected. The stresses resulting from the accelerating loads were all lower than 100 MPa, and a stress distribution similar to static loading was expected as the load was similar to the static loading, with the addition of a small component in the horizontal direction. The braking load significantly increased the stresses in the model in comparison to the static model, and were due to the addition of a horizontal force component of almost the same magnitude as the vertical component. The braking load produced the most noticeable effect on the stresses of the front trailer. This was due the additional load of the rear trailer, as previously discussed.

Finite element studies presented in Coker (2003) and Chutima *et al.* (2003) resulted in maximum Von Mises stress ranges of 94.7 to 184.8 MPa and 42.9 to 82.8 MPa. The stress range in Chutima *et al.* (2003) is larger, as these stresses occurred in the region of the pinned support of the fifth-wheel. The results in Coker (2003) correlate well with the Von Mises stress range obtained for static loading of 42.82 to 87.00 MPa. The measured stresses for a semi-trailer travelling over a variety of surfaces in Woodley and Piggot (1975) range from 99 to 185 MPa, which the author relates to a range of design factors of 1.2-2.4. This data also agreed well with the results obtained in this study, with the maximum Von Mises stress of 243.59 MPa corresponding to a design factor of 2.75.

Conclusion

The main chassis beam of a cane haulage vehicle has been optimised. This resulted in a vehicle that has a 15% reduction in tare mass in comparison to similar vehicles in Table 1. The final design is shown in Figure 8. The two main chassis beams are connected with cross-braces, and the bolsters are bolted on top of the upper flanges of the main chassis rails.

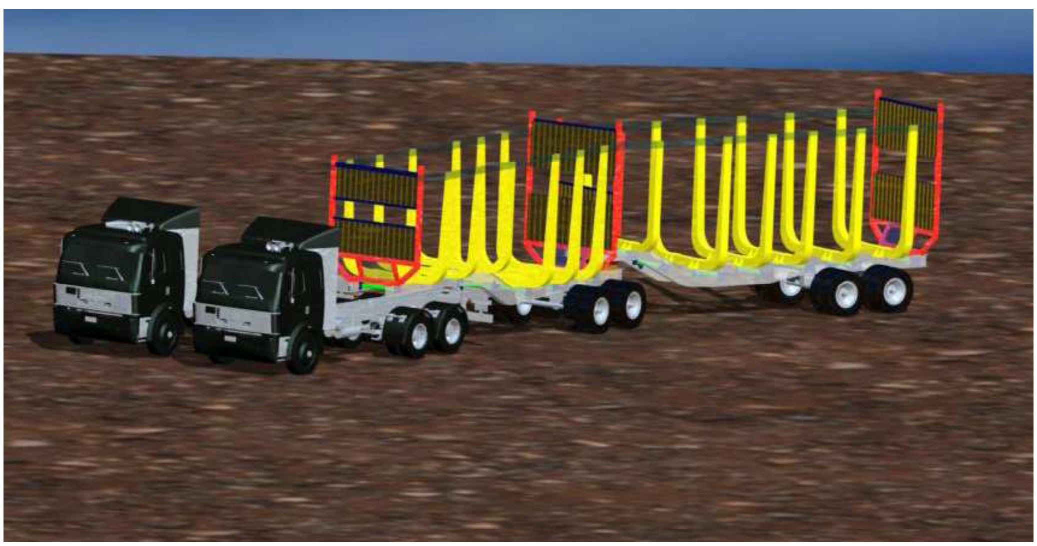

Figure 8. Simulation of the final design.

Cane haulage vehicles generally tend to operate under harsh conditions, carrying large payloads over rough terrain. The vehicle in this study was designed conservatively, with the worst case scenario considered for load cases, and relatively low stresses occurring in the chassis under these loads. This, in conjunction with the additional structure required to retain the cane, resulted in cane haulage vehicles being inherently heavier than other haulage vehicles, such as timber vehicles. The current trailer designs reached a state of optimisation through 'trial and error' methods. This is evident from the similarity in appearance of the current designs and the optimised design. The tare mass saving achieved through the optimisation of the design, while fairly substantial, is not a leap forward. To further increase the efficiency of sugarcane transportation, developments such as performance-based standards, onboard weighing systems and central tyre inflation will have to be considered.

Acknowledgments

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REFERENCES

Ang-Olson J and Schroeer W (2003). Energy efficiency strategies for freight trucking: Potential impact on fuel use and greenhouse gas emissions. Proceedings of the 81st Annual Meeting of the Transportation Research Board: Transportation Research Record.

Anon (2007). Wilde FEA Ltd. Case Study 63: Gas Transport Trailer Structural Assessment by Wilde FEA. [Internet]. Wilde FEA Ltd., Stockport, Cheshire, UK. Available from: www.wildefea.co.uk/consulting/casestudies/casestudies63/

Anon (2005a). Altair bus frame design – Federally funded transportation project aims at economy, ecology, and passenger comfort. Altair Engineering, (Troy, Michigan, USA)

Anon (2005b). PTC corporate. Pro/Mechanica Pro/Mechanica Help File – Structural and thermal simulation. [Internet]. PTC corporate, Needham, Massachusetts, USA. Available from: http://proe.ippd.ufl.edu/wildfire/html/usascii/promec/start.htm

Anon (2006a). HTM TransSolve Product Information, Hellberg Transport Management, [Internet]. Available from: http://www.HTM.co.za

Anon (2006b). Light tipper trucks from Gotha. Schmitz Cargobull AG – The Trailer Company. CargoBull News. [Internet]. Schmitz Cargobull, Horstmar, Germany. Available from: http://www.cargobull.com/en/news_dates/act_detail.php?news_id=20

Chetthamrongchai P, Auansakul A and Supawan D (2001). Assessing the transportation problems of the sugar cane industry in Thailand. Transport and Communications Bulletin for Asia and the Pacific, No. 70.

Chutima S, Kamnerdtong T and Aungkurabrut D (2003). A study of full-trailer and semi-trailer structures using finite element method. Proceedings of the 12th International Pacific Conference on Automotive Engineering, BITEC, Bangkok, Thailand. pp 111-118.

Clarke C (2005). FEA Information Resource Magazine. Building a better truck with VPD-Leyland Trucks. Finite Element Analysis. [Internet]. FEA Information Resource Magazine pages 8-11. Available from: http://www.feainfo.com/news_2005/aug_2005_feanews.pdf ; http://www.mscsoftware.com/success/details.cfm?q=285&Z=181&sid=359

Coker RA (2003). An investigation into the feasibility and application of fiber composites to flatbed semi-trailers. PhD Dissertation, University of Southern Queensland, Brisbane, Australia.

Harris MN and Naworocki PE (1984). Design analysis for heavy duty vehicles today and tomorrow. *Int J Vehicle Design* 5(1,2): 104-114.

Hogberg D (2001). Use of finite element method in trailer deck design. *J Materials Processing Technology* 117: 238-243.

Johansson I and Gustavsson M (2000). Volvo Truck Corporation. Proceedings of 2nd MSC Worldwide Automotive Conference, MSC, 2000: FE-based vehicle analysis of heavy trucks Part 1 Methods and Models . [Internet]. Volvo Truck Corporation, Göteborg, Sweden. Available from: http://www.mscsoftware.com/support/library/conf/auto00/index.cfm

Karaoglu C and Kuraly NS (2002). Stress analysis of a truck chassis with riveted joints. *J Finite Elements in Analysis and Design* 38: 1115-1130.

Karita K, Kohiyama Y, Kobiki T, Ooshima K and Hashimoto M (2003). Mitsubishi Motors. Mitsubishi Motors Technical Review, 2003, no 15: Development of aluminum frame for heavy-duty trucks. [Internet]. Mitsubishi Motors, Minato-Ku, Tokyo, Japan. Available from: www.mitsubishi-motors.com/corporate/about_us/technology/review/e/pdf/2003/15E_13.pdf

Lan F, Chen J and Lin J (2004). Comparative analysis for bus side structures and lightweight optimisation. Proceedings of the Institute of Mechanical Engineers, Part D. *J Automobile Eng* 218(10): 1067-1075.

Lathen S (1998). Prospects for reductions in truck and bus fuel consumption in the UK. *Int J Vehicle Design* 20(1-4): 283-291.

Maasdam J (1999). DAF Trucks. Proceedings of the 1999 MSC Worldwide Automotive Conference, MSC, 1999: A finite element vehicle analysis library for commercial vehicles. [Internet]. DAF Trucks, NV, Eindhoven, The Netherlands. Available from: www.mscsoftware.com/support/library/conf/auto99/p02799.pdf

Poh KW, Dayawansa PH, Dickerson AW and Thomas IR (1999). Steel membrane floors for bodies of large rear-dump mining trucks. *J Finite Elements in Analysis and Design* 32: 141-161.

Sharp J, Pesbeck E, Nelson D, McLellan S, Ashdown G (2000). Orion Bus Ltd. Proceedings of the 15th MSC European ADAMS user conference, 2000: Virtual prototyping of a transit bus to predict service life.. [Internet]. Orion Bus Ltd, Oriskany, NY, USA. Available from: www.mscsoftware.com/support/library/conf/adams/euro/2000/OrionBus_Transit_Bus.pdf

Taylor GWR (1999). The potential for GHG reductions from improved use of existing and new truck technology in the trucking industry. Transport Report, National Climate Change Transportation, Trucking Sub-Group.

Woodley CC and Piggot BR (1975). Design data for heavy vehicles. Proc IEEE Conference on Electrical Engineering Problems in the Rubber and Plastics Industries: Stress, Vibration and Noise Analysis in Vehicles. Institute of Physical Stress Analysis, Birmingham, England. pp 473-481.