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Lane-Width Requirements for Heavy Vehicles

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Abstract

The ability of a heavy vehicle to remain within a specified lane width is of prime importance to its acceptability in the traffic stream. Tracking ability describes how well a heavy vehicle's trailing unit (last trailer) tracks along the same path as the lead unit (prime-mover or rigid truck); it is one of several important considerations when assessing the suitability of routes for access by heavy vehicles. To safely accommodate the tracking performance of heavy vehicles on the road network generally requires more lane width than is necessary for other road users. Only some routes will be suitable for heavy vehicle use. A performance-based approach to estimating lane width requirements for heavy vehicles travelling along straight paths has been developed using state-of-the-art computer modelling techniques. Full-scale tests were first conducted covering a range of speed and road unevenness conditions, and two methods of measuring tracking ability were demonstrated. Test results for an A-Double road train were used to verify and validate predictions from computer simulations, and to confirm the general modelling method. Computer models of a range of generic, commonly used heavy vehicles were then created and tested. The aim was to determine dimension limits for heavy vehicle tracking on straight paths that would cover all possible situations that might occur under legal mass and volume loading schedules. The findings from this research suggests most of these heavy vehicles studied could comfortably travel along roads that have a useable lane width of 3.5m; however the largest two exceed this limit at the higher of the two speeds investigated (90km/h). The research found tracking ability was principally dependent on road cross-slope, vehicle configuration, length, and speed.

1. INTRODUCTION

Current methods for selecting heavy vehicle routes and for identifying vehicles that can operate on select routes are based largely on the subjective judgements of regulators and on knowledge of the performance of existing heavy vehicles. In Australia, specifications for heavy vehicle tracking, for example, have not changed significantly for more than 15 years and their origins can be traced back to studies performed in the USA in the 1970s (Alberta Department of Highways and Transport, 1970; NAASRA, 1978; Roads and Traffic Authority, 1996). These methods and specifications are difficult to apply with confidence to new and innovative heavy vehicle configurations, and at times they may not be meaningful or appropriate.

A general method has been developed to determine lane width dimension limits for heavy vehicles using a performance-based approach. The tracking behaviour of a road train was measured in a series of full-scale tests to verify and validate predictions from computer simulations. Computer modelling was then used to determine lane width requirements for a range of commonly used heavy vehicles.

2. FULL-SCALE TESTS AND MEASUREMENTS

2.1 Test Vehicle and Instrumentation

Full-scale tests were conducted on an A-Double road train (shown in Fig. 1) and the lateral dynamic responses of the hauling and trailing units were measured due to excitations from road surface unevenness at three different test speeds (60, 75 and 90km/h).

Two methods were used for measuring tracking response; one using a vehicle-mounted video camera, the other based on measurements of the vehicle's lateral acceleration taken at a number of locations.

2.1.1 Video-Based System

A video camera mounted on the rear of the trailing unit recorded an image of a water trace left on the pavement by a purpose-built device attached under the steer axle of the hauling unit. The offset of the water trace in the video image was later digitised to provide an estimate of the lateral position of the trailing unit measured relative to the hauling unit's steer axle centre. A more detailed description of the system can be found in Prem et al (1999).

Fig. 2 is a typical example of the measurements showing the relative lateral displacement and run-to-run variability for the A-Double travelling at 60km/h. The variation in the response between runs is most likely due to speed changes along the test section and small variations in driver steering activity that will influence the paths followed by the prime mover and the trailers. The range of relative lateral displacement of the rear of the trailing unit when measured relative to the water trace is about 250mm.

2.1.2 Accelerometer-Based System

Accelerometers installed at the centre of gravity (CG) of the prime mover and at both the CG and rear of the last trailer measured lateral acceleration. The signals from the accelerometers were later double integrated using a digital filter similar to that successfully employed in the ARRB TR profilometer (Prem, 1989) to provide estimates of lateral position[A]. Prior to the double integration the lateral acceleration signals were corrected for vehicle roll angle. This roll introduces a component of gravity that is sensed by the accelerometer whenever its measurement axis rotates out of the horizontal plane. The roll angles of the hauling unit and the trailer were determined from the cross-slope profiles measured separately (see later) and measurements taken with non-contact height sensors mounted on each side of the hauling unit and on each side of the trailing unit.

Fig. 3 shows the close agreement between the measurements taken from the video system and those from the accelerometer-based system. When compared to the video system, the accelerometer-based system is simpler to install and the data processing requirements are considerably easier. With further refinement, the system could serve as an efficient method of testing vehicles on a routine basis.

2.2 Road Profiles and Unevenness

Road profile measurements were taken with an ARRB TR Walking Profiler (WP) (Auff et al, 1995; ARRB Transport Research Ltd., 1996) along the travelled wheelpaths on each of three test sections. Road profile height measurements were taken every 241mm (9.5") along each test section in both the inner (driver's side) and outer wheelpaths. In addition, cross-slope measurements were taken every 100m to establish the height of the right wheelpath profile relative to the left wheelpath profile. These profiles were later used to create a three-dimensional surface representing each test section that was used in the computer simulations.

The measured wheelpath height profiles for Test Section C are shown in Fig. 4(a). The inner wheelpath (driver's side) is at a slightly higher elevation than the outer wheelpath. Also, the road has a slight down grade from the start to a distance of about 250m. The cross-slope profile for the same section, shown in Fig. 4(b), has an average cross-slope of about -4% (sloping down from right to left) and a range from about -2% to -6%.

[A] There is a subtle difference in interpretation of the lateral displacement measurements between the video- and accelerometer-based systems. The accelerometer-based systems measure lateral position relative to a nominally ground based ("inertial") reference frame, whereas the video system measures the lateral position of the rear unit relative to the hauling unit when the hauling unit was at the same location along the path as the trailing unit. The two systems will produce essentially identical outputs when the lateral motion of the hauling unit is small.

For long vehicles travelling on straight paths, cross-slope will have a significant influence on the lateral position of the trailers relative to the hauling unit. In order for a vehicle with pneumatic tyres to stay on a road with cross-slope, it must point slightly up slope at an angle to the direction of travel. This will cause a slip angle to develop at the tyres producing a side force directed up-the-slope that will balance the down-the-slope component of gravity. The required slip angle is extremely small, of the order of about 0.1 degrees for each percent of cross slope, depending largely on the cornering stiffness of the tyres. However, even this small angle will produce a constant lateral offset of about 350mm between the two ends of a 50m-long road train on a road that has a 4% average cross-slope. This apparent misalignment would easily exceed the dimensional tracking limit of 100mm recommended by NAASRA (1978).

A variety of measures and methods exist for characterising road surface unevenness, the most widely used are the International Roughness Index, or IRI (Sayers et. al., 1986), and in Australia the NAASRA roughness. However, both these indices are intended to provide a measure of pavement rideability and they may not cover the full range of unevenness, or capture the key features in a profile that will influence heavy vehicle tracking[B]. Therefore, in addition to the IRI, several other unevenness measures were devised which are shown in Table 1. They include the absolute value of the difference between the outer and inner wheelpath IRIs ($|\Delta IRI|$, or "delta IRI"), and the average and standard deviation of the cross-slope profiles.

The unevenness characteristics of the test sections that are shown in Table 1 can be summarised as follows:

i) the highest IRI occurs in the inner wheelpath of Test Section C;
ii) the lowest IRI occurs in the outer wheelpath of Test Section A;
iii) the largest difference between inner and outer wheelpath IRI occurs on Test Section B; therefore, delta IRI has its highest value on Test Section B;
iv) Test Section B has the highest average cross-slope, followed by Test Section C and then A;
v) Test Section B has the highest cross-slope standard deviation, followed by Test Section A and then C.

3. FULL-SCALE TEST RESULTS

Measurements were taken at three speeds (60, 75 and 90km/h) along each of the three test sections. All the video recordings taken on the A-Double were processed, the relative lateral displacements were calculated. A sample of these data were analysed and found to

[B] Whilst the IRI is accepted as a reliable low-cost measure of relative comfort for occupants of passenger cars, there are a number of anecdotal instances of truck drivers complaining of poorer ride quality than indicated by traditional roughness data. In order to better represent truck response in asset management systems, a road profile based Truck Ride Index (TRI) has been developed, similar in concept to the IRI, that is tuned to the vertical vibration response of trucks (Prem, Ramsay and McLean, 2000).

have an approximately normal probability distribution. On the strength of this finding, lateral displacement was taken to be a normally distributed random variable and the sample mean (μ) and standard deviation (σ) were considered appropriate measures for characterising the overall response. It is useful to recall that for a normally distributed random variable approximately 68% of sample points fall within $\pm 1\sigma$ of the mean, 95% are within $\pm 2\sigma$, and 99% will lie within $\pm 3\sigma$ of the mean.

Fig. 5 shows standard deviations for each set of runs on each test section at the various test speeds. The relative lateral displacement of the rear of the trailing unit can be seen to increase with speed, and the largest lateral displacement occurs on Test Section B, followed by Test Sections C and A, respectively.

A review of Table 1 will show that the trends in Fig. 5 follow the trends in the cross-slope unevenness measures (average and standard deviation) and delta IRI. That is, on Test Section B where the lateral displacement response is greatest the cross-slope unevenness and delta IRI is also largest. This is examined in more detail in Section 4.4 of this paper.

Measurements taken with the accelerometer on the hauling unit were used to calculate the lateral displacement of the A-Double prime mover. Fig. 6 shows that the variations in lateral displacement are approximately constant in magnitude on each test section but show a slight increase with speed, perhaps indicating it is more difficult to maintain tracking precision along a straight path at higher speed. The total range for lateral displacement can be determined from the standard deviations, and the data in Fig. 6 suggest the driver was able to maintain the prime mover to within ±60mm to ±75mm (within $\pm 3\sigma$) of a straight path.

4. VALIDATION OF COMPUTER MODELLING

4.1 Model of Test Vehicle

A 3-dimensional full-vehicle computer model of the A-Double was created with the ADAMS multi-body dynamics simulation package (Mechanical Dynamics Inc., 2000) and its outputs compared to measured responses. A perspective view of the computer model is shown in Fig. 7. Validation of the computer model in a standard lane change manoeuvre (Society of Automotive Engineers, 1993) was previously performed by comparing measurements from full-scale tests with predictions from computer simulations (Elischer and Prem, 1997). However, the lane change simulations were performed on a smooth, flat, idealised surface, which was acceptable for that manoeuvre because the steer inputs and lateral motions in a lane change are relatively large in comparison to the effect of road surface unevenness on the lateral response. Because the primary source of disturbance to vehicle lateral motion considered in this paper is road surface unevenness, a separate validation was required that included the influence of unevenness.

4.2 Road Surface Model

Three separate 3-dimensional surfaces were created in ADAMS from the measured unevenness profiles. The surfaces include unevenness that cause vertical vibration as well as the cross-slope that would cause the vehicle to eventually track off the road in the absence of a steer controller.

4.3 Validation

Validation comparisons were performed at the same speeds as the full-scale tests on each of the three test sections. The locations of measuring instruments in the simulations and full-scale tests were identical, and the response data from the simulations were processed identically to the response data in the full-scale tests. The steering controller was adjusted to produce approximately the same magnitude of lateral motions in the prime-mover that occurred in the full-scale tests.

Fig. 8(a) compares the measured responses in three separate runs with the predicted response from the computer model. The prediction from the computer model follows the measured responses closely over most of the run, both in terms of magnitude and frequency content (analysed separately). In some regions the agreement is excellent, as revealed by Fig. 8(b), which shows that the predicted response over the segment from 300 to 700m is within the run-to-run variability of the measured responses. Further comparisons between the measured and predicted responses can be found in Prem et al (1999), together with a detailed discussion of a range of possible sources of error that may account for some of the differences.

In summary, the predictive capability of the vehicle dynamics modelling system has been validated in the context of this work, and provides a reasonable basis for the assessment of heavy vehicle tracking.

4.4 Response to Cross-Slope

From the full-scale tests and simulations it was found that the largest relative lateral displacement response occurred on the test section with the greatest cross-slope unevenness. Comparing Figs 4(b) and 8(a) reveals that the lateral displacement response closely follows the cross-slope profile; this finding is consistent for all the runs. Therefore, the lateral dynamic tracking response under the conditions described in this paper is largely controlled by the cross-slope profile.

This finding has a range of implications. For example, the traditional measures of road surface unevenness, such as IRI, whilst providing a measure of the vertical vibration in vehicles tells us little about the tracking performance of heavy vehicles. The cross-slope profile, which is not measured in network-level unevenness surveys and is rarely measured at all, could be a very useful parameter for assessing the ability of a particular route to accommodate heavy vehicles when tracking is a prime consideration.

Given there are very few cross-slope profile data in existence, and it would not be easy to collect at the network level, the difference between the outer and inner wheelpath IRIs could be considered a surrogate. The ranking of Test Sections based on delta IRI, for example, is consistent with the ranking based on the measured heavy vehicle responses. IRI for outer and inner wheelpaths are collected in routine network surveys and these would be available for immediate application for route access assessment. However, further research should be undertaken to support this proposal.

Additional simulations were analysed to develop a better understanding of the vehicle factors that influence tracking. These are described in detail in Prem et al (1999), revealing that, at the basic level, tracking would depend on the vertical load supported by each tyre, the length of the vehicle, and the cornering stiffness of the tyres. Further, the increase lateral displacement with speed was found to be a direct result of the increase in tyre slip angle, and hence tyre side force necessary to balance the lateral inertia forces that increase with speed.

5. LANE WIDTH REQUIREMENTS

5.1 Generic Heavy Vehicles

Computer models of a range of commonly used Australian heavy vehicles were created and separate simulations performed at two test speeds (60 and 90km/h) on the road file created for Test Section B. Dimensions for most of the heavy vehicles were taken from Austroads (1995), a set of turning templates that are used primarily for intersection design purposes. Dimensions for vehicles not listed in Austroads (1995), specifically the Truck/Trailers, the 19m B-Double, the B-Triple and the Rigid-plus-Three were based on dimensions typical of the Australian heavy vehicle fleet. All vehicles were loaded to their maximum legal limit at maximum volume by assuming a uniform density payload and maximum height of 4.3m. All axle group loads were at their respective maximum legal limits at the time, except the trailer axle groups on the truck/trailer models, which had the trailer-to-truck mass ratio requirement to satisfy.

The generic heavy vehicles should be considered worst-case vehicles operating under worst-case conditions to produce maximum lateral displacements. The aim was to determine dimension limits on tracking that would cover all possible situations occurring under the current legal mass and volume loading schedules. In regard to this, the generic A-Double differs to the vehicle used in the full-scale tests, which was based on a specific, real vehicle with a lower payload CG height and axle loads, and would perform better than its generic counterpart.

Just as the generic vehicles were created using generalised dimensions, masses, suspension and tyre characteristics, models of specific heavy vehicles can be created as a separate exercise and evaluated under any conceivable operating conditions.

The range of vehicles examined in this study and their general characteristics are summarised in Table 2.

5.2 Lateral Displacement Response Characteristics

Response statistics for the generic heavy vehicles models are summarised in the "bar and whisker" plots shown in Fig. 9. The bars represent the average lateral displacement of the rear-end of the rearmost unit and essentially show the lateral offset due to the average cross-slope of the road. All averages are negative indicating the trailers hold a position on the cross-slope to the left of the hauling unit. The whiskers represent $\pm 3\sigma$ increments, and reflect the magnitude of the dynamic response of the rear trailer about the mean. In all cases $\pm 3\sigma$ of lateral displacement is enough to bring the rear trailer in line with the hauling unit at times. Motions that increase lateral displacement to the kerbside (more negative) increase swept width significantly.

Fig. 9 shows the most responsive vehicles are, in order of decreasing responsiveness, the Rigid-plus-Three, the A-Triple, the A-Double, and the B-Triple. An increase in speed has the greatest effect on the Rigid-plus-Three and the A-Triple. Speed has a small effect on the A-Double. The 19m and 25m B-Doubles have very similar dynamic responses as revealed by the standard deviation, but the longer 25m B-Double would occupy slightly more lane width. The 12-2S2 Truck/Trailer requires slightly less lane width than the 12-1S2, and the effect of speed on both vehicles is small. The 19m B-Double is almost equivalent to the Prime-Mover/Semi-Trailer of the same length, but the B-Double is slightly more sensitive to speed.

5.3 Specification of Lane Width

5.3.1 Lateral Displacement Excursions

Fig. 9 shows that the rear trailer of all of the vehicles will spend the majority of time to the left (kerbside) of the hauling unit (located at zero on the horizontal axis). Occasional excursions to the right of the hauling unit of up to about 100mm will occur for almost all the vehicles, with the exception of the Rigid-plus-Three and the A-Triple at the higher speed which have excursions in excess of 250mm.

5.3.2 Lane Width

Lane width requirements can now be defined by adding the maximum legal width for heavy vehicles (2.5m in Australia) to the lateral displacement results shown in Fig. 9. Fig. 10 shows the lane width requirements for each heavy vehicle, and suggests that most could travel comfortably along roads that have a useable lane width of 3.5m, except for the Rigid-plus-Three and the A-Triple at the higher of the two speeds. NAASRA (1972) and Austroads (1989) recommends lane widths of 3.7m on freeways and 3.5m on rural roads, stating that this allows large vehicles to pass without "instinctive" lateral movement. The common lane widths for National Highways in Australia are in the range 3.5 to 3.7m.

6. ROUTE SELECTION CONSIDERATIONS

Assuming a useable lane width of 3.5m on a sealed two-lane carriageway, Fig. 9 shows encroachment into the adjacent lane would be unlikely for most of the generic heavy vehicles studied (except the Rigid-plus-Three and the A-Triple). This assumes the driver has positioned the front right corner of the hauling unit at least 200mm to the left of the centre of the carriageway. This slightly offset position within the lane would increase the likelihood of the rearmost axle group occasionally running off the edge of the lane and off the edge of the seal, as depicted for the A-Double in Fig. 11.

For the Rigid-plus-Three and the A-Triple, an offset from the right-hand lane edge of 300mm would be required to ensure unlikely encroachment into the adjacent lane. However, if the useable lane width is 3.5m this would leave the left-hand side of the last trailer's rear-axle group (and possibly the axle-groups closer to the hauling unit as well) running off the edge of the seal. For much of the time the rear axle group would be running along or off the edge of the seal. This situation is undesirable from a safety perspective, and it would also cause damage to the seal and road shoulder and lead to an increase in road maintenance and heavy vehicle operating costs.

7. SUMMARY AND FURTHER ISSUES

7.1 Summary

Two methods of measuring the tracking performance of heavy vehicles have been developed and applied in full-scale tests. The field measurements showed that the tracking response was largest on the test section that had the largest average cross-slope and variation in cross slope profile.

The predictive capability of the vehicle dynamics modelling system has been validated and provides a reasonable basis for the assessment of heavy vehicle tracking.

Computer models were created of a range of generic Australian heavy vehicles and their tracking performance and lane width requirements were determined. The most dynamic vehicles, in order of decreasing tracking responsiveness, were found to be the Rigid-plus-Three, A-Triple, A-Double, and B-Triple. Increases in speed were found to have the greatest effect on the Rigid-plus-Three and A-Triple. Findings of this research suggest that most of the heavy vehicles evaluated could travel comfortably along roads that have a useable lane width of 3.5m, except the two 53.5m long vehicles which would require about 3.7m of lane width.

The ranking of test sections (from best to worst) based on "delta IRI" is largely consistent with the ranking of the sections from the measured heavy vehicle tracking responses and direct measures of cross-slope characteristics (mean and standard deviation). IRI for outer and inner wheelpaths have been collected in routine network-level roughness surveys and could be used to calculate delta IRI and provide an indication of cross-slope profile unevenness for route access evaluation. However, further study of road cross-slope characteristics and its relationship with delta IRI is recommended.

7.2 Further Issues

The results presented in this paper for lane width are based on straight path travel, two test speeds, and the unevenness characteristics of one road section. Lane width specifications on roads with geometry other than straight path would require a different set of test conditions, and would need to consider vehicle off-tracking (high- and low-speed), and the influence of superelevation, complex transitions and unevenness. The method and approach described in this paper and the models that have been created are well suited to the task.

If the lane widths recommended in Fig. 10 are to be adopted, more profiles from a selection of roads that are known to contribute to poor tracking of heavy vehicles should be collected and analysed, and the recommendations shown in Fig. 10 should be confirmed.

Roads for further study could be identified in the first instance from network level unevenness data using the delta-IRI measure described in this paper. Further study of road cross-slope characteristics is recommended so that new knowledge can be developed and applied to both the study of heavy vehicle performance and the determination of route access criteria.

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REFERENCES

ALBERTA DEPARTMENT OF HIGHWAYS AND TRANSPORT. Report on the Testing of Triple Trailer Combinations in Alberta. Alberta Department of Highways and Transport, 1970.

AUFF, A.A., TYSON, G. and CHOUMMANIVONG, L. Evaluation of the Road Roughness Measuring Capability of ARRB's Prototype Walking Profilometer. Research Report ARR 266. ARRB Transport Research Ltd: Vermont South, Vic., Australia, 1995

AUSTROADS. Rural Road Design: A Guide to the Geometric Design of Rural Roads. AUSTROADS Publication No. AP-1/89. (formerly NAS-62), Sydney, Australia, 1989.

AUSTROADS. Design Vehicles and Turning Path Templates. AUSTROADS Publication No. AP-34/95. Austroads: Sydney NSW, Australia, 1995.

ARRB TRANSPORT RESEARCH LTD. Multi-Laser Profiler, Two-Laser Profiler and Walking Profiler. ARRB Transport Research Product Brochures. ARRB Transport Research Ltd: Vermont South, Vic., Australia, 1996.

ELISCHER, M.P. and PREM, H. Validation of Heavy Vehicle Dynamics Modelling using ADAMS - Lane Change Manoeuvre. Contract report OC6053V (restricted circulation). ARRB Transport Research Ltd: Vermont South, Vic., Australia, 1997.

MECHANICAL DYNAMICS INC. *Internet Website – http://www.adams.com/* Mechanical Dynamics, Inc., Ann Arbor, MI, USA, 2000.

NATIONAL ASSOCIATION OF AUSTRALIAN STATE ROAD AUTHORITIES A Study of the Operation of Large Combination Vehicles (Road Trains). Working Party Report No. 1. National Association of Australian State Road Authorities, July, 1978.

NATIONAL ASSOCIATION OF AUSTRALIAN STATE ROAD AUTHORITIES Guide policy for geometric design of freeways and expressways. NAASRA: Sydney, Australia, 1972.

PREM, H. The ARRB Highway-Speed Road Profiling System: Description, Technical Manual and User's Guide. Report to Australian Road Research Board, Vermont South, Vic., Australia, 1989. (Restricted circulation.)

PREM, H., RAMSAY, E.D., FLETCHER, C.A, GEORGE, R.M. and GLEESON, B.P. Estimation of Lane Width Requirements for Heavy Vehicles on Straight Paths. Research Report ARR 342. ARRB Transport Research Ltd., Vermont South, Vic., Australia, 1999.

PREM, H., RAMSAY, E.D. and McLEAN, J.R. A Road Profile Based Truck Ride Index (TRI). 6th Heavy Vehicle Weights and Dimensions Symposium, Saskatoon, Saskatchewan, Canada, June 18-22, 2000.

RAMSAY, E.D, PREM, H. and PETERS, R.J. An International Heavy Vehicle Nomenclature System.. 6th Heavy Vehicle Weights and Dimensions Symposium, Saskatoon, Saskatchewan, Canada, June 18-22, 2000.

ROAD AND TRAFFIC AUTHORITY. Permit Orders for the Operation of B-Doubles, Road Trains & 4.6m High Vehicles. Roads and Traffic Authority Publication RTA 45070688A, Sydney, Australia, 1996.

SAYERS, M.W., GILLESPIE, T.D. and QUEIROZ, C.A.V. The International Road Roughness Experiment: Establishing Correlation and a Calibration Standard for Measurements. World Bank Technical Paper Number 45. World Bank: Washington DC, USA, 1986.

SOCIETY OF AUTOMOTIVE ENGINEERS A Test for Evaluating the Rearward Amplification of Multi-Articulated Vehicles. SAE J2179, Society of Automobile Engineers: Warrendale, PA, USA, 1993.

TABLES AND FIGURES

TABLE 1 - Measures of Road Unevenness

Test Section	Nominal Length (m)	IRI (m/km)		|ΔIRI| (m/km)	Cross-Slope (%)	
		Outer	Inner		Average	Standard Deviation
A	1200	2.94	3.01	0.07	-3.19	0.98
B	1000	4.36	3.85	0.51	-4.49	1.18
C	1000	4.38	4.53	0.17	-4.00	0.68

TABLE 2 - Generic Heavy Vehicle Fleet used in this Study

Vehicle	Configuration[1)]	Length (m)	GCM (t)
Prime-Mover/Semi-Trailer	12S3	19	42.5
Truck/Trailer (3-axle dog)	12-1S2	16.8	45
Truck/Trailer (4-axle dog)	12-2S2	20	50
A-Double	12S3-2S3	36	79
A-Triple	12S3(-2S3)2	53	115.5
19m B-Double	12(S2)2	19	55.5
25m B-Double	12(S3)2	25	62.5
B-Triple	12(S3)3	33	82.5
Rigid-plus-Three	12(-2S3)3	53	132

Notes:

1) Description is based on the system proposed by Ramsay, Prem and Peters (2000).

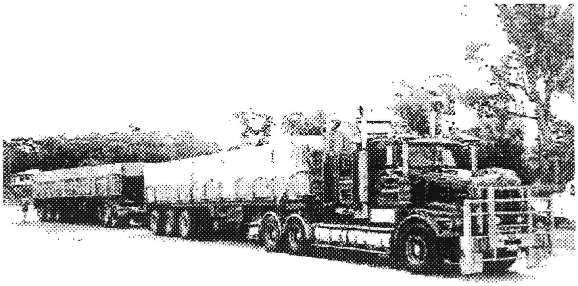

Fig. 1 The A-Double test vehicle.

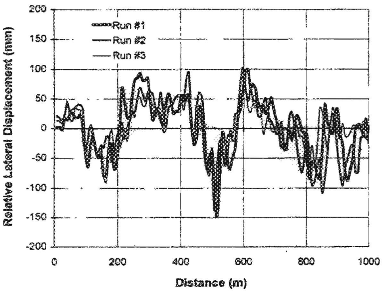

Fig. 2 Lateral displacement from the video-based system - 60km/h on Test Section C.

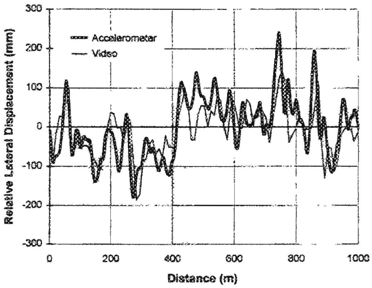

Fig. 3 Comparison of video- and accelerometer-based systems - 75 km/h on Test Section B.

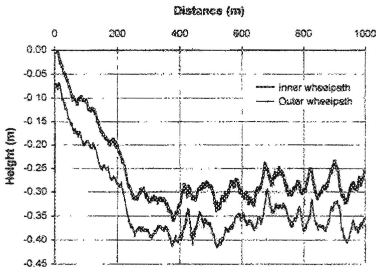

Fig. 4(a) Wheelpath profiles measured on Test Section C.

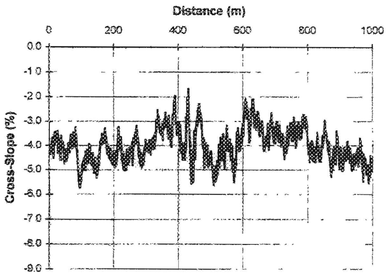

Fig. 4(b) Cross-slope profile measured on Test Section C.

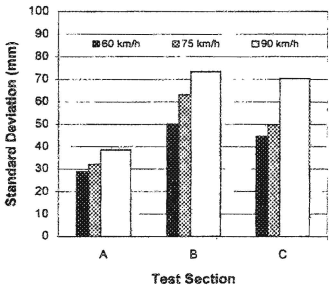

Fig. 5 Relative lateral displacement of rear unit from video system on the A-Double.

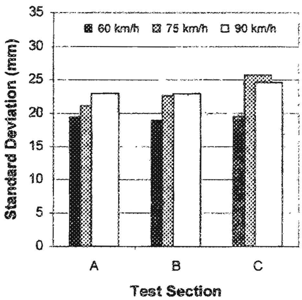

Fig. 6 Prime-mover lateral displacement from the accelerometer-based system.

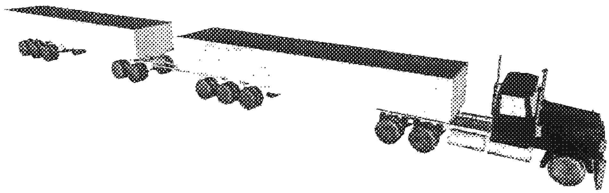

Fig. 7 Computer model of the A-Double test vehicle.

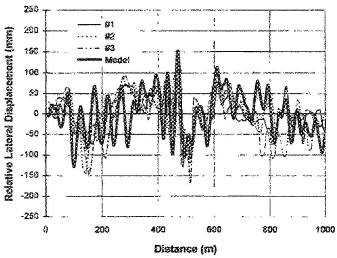

Fig. 8(a) Comparison of measured with predicted on Test Section C at 75 km/h.

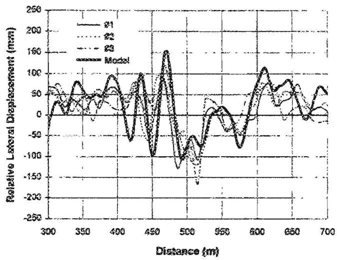

Fig. 8(b) Comparison of measured with predicted over 300 to 700m interval on Test Section C at 75 km/h.

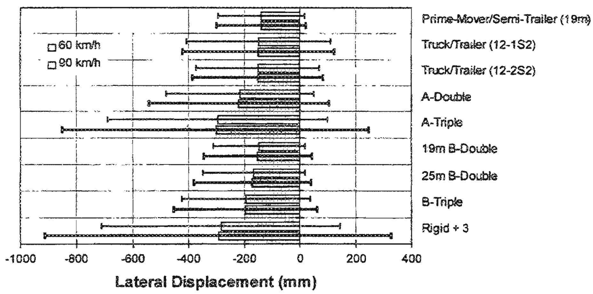

Fig. 9 Bar and whisker plot showing lateral displacement of rear trailer ($\mu \pm 3\sigma$). The hauling unit is located at the origin (zero).

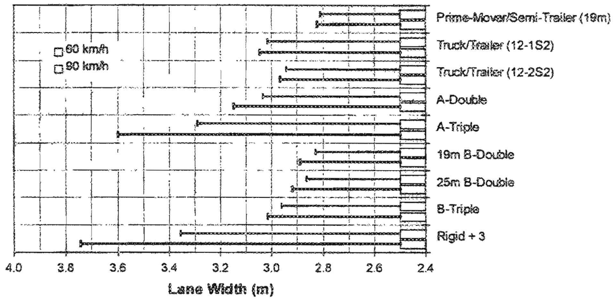

Fig. 10 Estimated lane width requirements for a range of heavy vehicles.

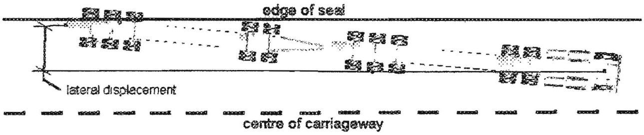

Fig. 11 Effect of cross-slope on position of rear trailer axle-group - shown travelling along the edge of the seal with hauling unit slightly to one side of the lane centre.