DYNAMIC WHEEL LOADS OF HEAVY VEHICLES – PRELIMINARY ANALYSIS

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Abstract

There is much debate regarding the nature of the dynamic forces that heavy vehicles apply to pavements and the potential detrimental effects that these forces have on pavement performance. It has also been suggested that new generation heavy vehicles should be allowed to carry higher axle loads because of their more efficient design and operation. However, there is a lack of knowledge regarding the nature of these forces and their impact on pavement performance. Infrastructure owners and regulators need better information regarding the relationships between dynamic loading and pavement damage if they are to make more informed decisions regarding the appropriate mass limits for heavy vehicles.

This paper outlines the investigation into a low-cost repeatable measurement system, and preliminary analysis undertaken through Austroads project AT1480: Measurement and Analysis of Dynamic Wheel Loads. (Austroads, 2012).

Keywords: Dynamic wheel loads, heavy vehicles, strain gauge, load measurement, axle loads

1. INTRODUCTION

There is a need to improvement the understanding of the relationships between the characteristics of heavy vehicles operating on the Australasian road network, the dynamic forces that these vehicles apply to the pavement surface and the potential impact on the structural and functional performance of the road network, both at the project level and the network level. The development of relationships which more accurately predict the dynamic forces applied to a pavement, and their effect on network performance, will not only lead to a better understanding of current operating conditions, but also improved confidence in the ability of road authorities and regulators to provide the right pavements and heavy vehicles for Australasia.

The paper describes some outcomes from Austroads project AT1480: Measurement and Analysis of Dynamic Wheel Loads (Austroads 2012), whose objectives were to broadly:

- continue on from previous development of a low cost method for accurately quantifying the dynamic wheel loads of heavy vehicle trailers (Austroads, 2009)

- collect and analyse dynamic wheel load data to help quantify the relationship between dynamic loading of the pavement, and the pavement and vehicle characteristics.

2. DETERMINATION OF A LOW-COST REPEATABLE MEASUREMENT SYSTEM FOR DYNAMIC WHEEL LOADS

One of the main objectives of this project was to develop a method and system for the measurement of dynamic wheel loads on heavy vehicles. This system needed to meet a few key criteria:

- repeatable
- reasonably high accuracy
- low cost
- portable (for use on a large number of heavy vehicles and trailers)

Previous work (Austroads, 2009) had identified measurement of tyre deflection as showing good potential for meeting these criteria. The development process originally focussed on the recommendations in Austroads (2009) and in resolving the initial limitations of the laser transducer system developed to date. As work progressed, however, it became clear that in addressing these limitations the system was becoming more complex, costly and burdensome. A system based on strain gauges and accelerometers fitted to the axle, which is widely accepted as a reliable and repeatable system, and which is being used as a reference measurement, was adopted as the system to use. As an alternative to using strain gauges and accelerometers, a preliminary investigation into the use of airbag pressure to estimate dynamic wheel loads was also conducted. The paper documents the development process and the key initial findings in relation to the accuracy of each method.

2.1. Tyre deflection measurement system

The tyre deflection measurement system works on the basic theory that the tyre will deflect proportional to the vertical load placed upon it (over a certain range). A laser transducer was attached to the wheel, and aligned concentrically with the point of rotation to measure the vertical distance between itself and the pavement surface, which will reduce with an increased vertical load, as shown in Figure .

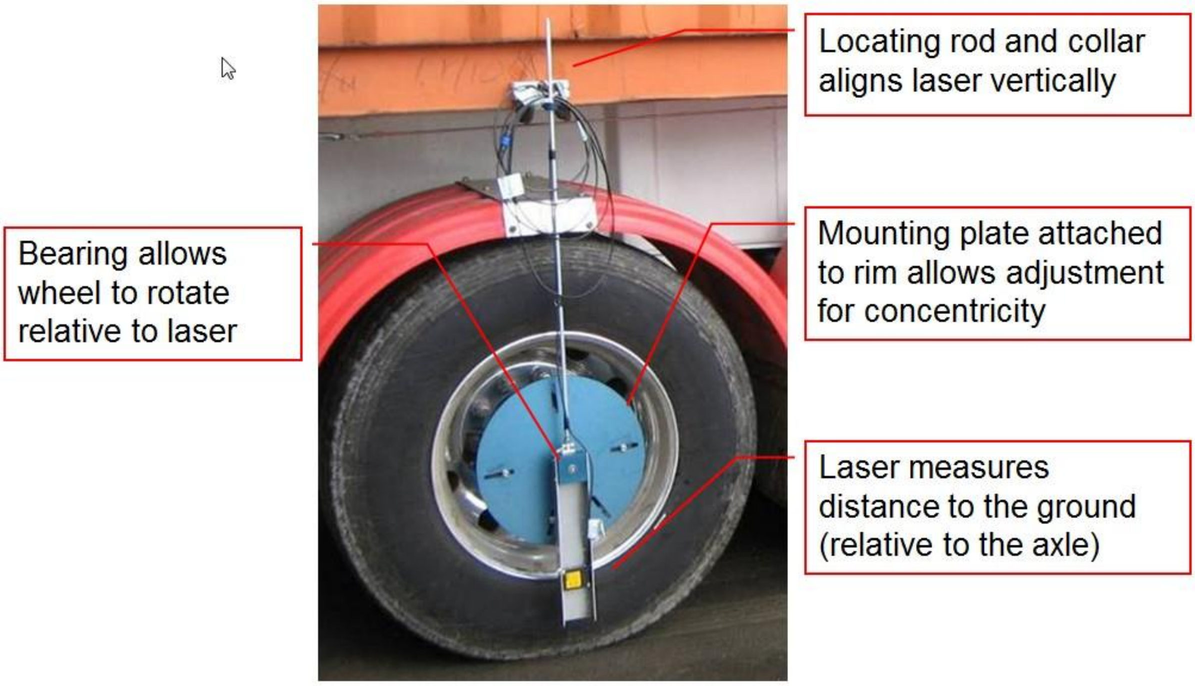

Figure 1 - Laser transducer measurement system

During its development, it became increasingly clear that the laser distance measuring system was becoming considerably more complex and expensive, and thus moving away from the objective of being a low-cost tool for reliably measuring dynamic wheel loads. A number of factors have contributed to this as outlined in Table 1.

Table 1 - Factors contributing to increased complexity and expense of laser measuring system

Issue	Description	Resolution/Effects
Longitudinal oscillations	Oscillations introduce significant errors to the measurements as distance will be changed when laser is not vertical.	Add bracing arm: increase in installation time. The need to measure axle rotation requires more sensors, increasing costs, installation time and complexity. Reduce/remove run-out: possibility of using specialised wheel rims (increased cost and installation time, reduction in portability).
Lateral offset	Differences between the wheel path and the path the laser is viewing can lead to erroneous measurements (e.g. wheels are in a rut, but laser is reading outside the rut; the shorter distance read by the laser will infer a larger wheel	Add extra lasers to correct: adding extra lasers (one reading the wheel path, and one in the 'laser path') will help provide a correcting signal; however, costs, installation and processing time, and

Issue	Description	Resolution/Effects
	load than is being experienced).	complexity are all increased.
Laser response	The laser units used to date have been shown to lack the response characteristics required for this type of tool.	Use higher quality laser: adds significant costs, and due to increased size and weight may lead to increased mounting assembly failures. Additional safety precautions are required.

The laser transducer based method for estimating dynamic wheel loads identified in Austroads (2009) was suitable as a first order estimate of dynamic wheel loads; however, limitations meant it did not offer the level of accuracy sought for many of the types of research envisaged for the system. Significant efforts were made to overcome the limitations of the laser method; however, these ultimately made the system too expensive and complex to warrant use, in comparison to the traditional and accepted method of using strain gauges with accelerometers, which offers relatively high accuracy.

2.2. Strain gauge and accelerometer measurement system

The system of using strain gauges on a vehicle's axle to measure the vertical force being transmitted through the wheel hubs and tyres, complemented with accelerometers to account for the inertial forces outbound of the strain gauges' position is a well-established method of measuring wheel forces. The accuracy, reliability and repeatability characteristics of these measurement systems have been widely published and, throughout the project, such a system (shown in Figure 2) was used for validating the laser distance measurements.

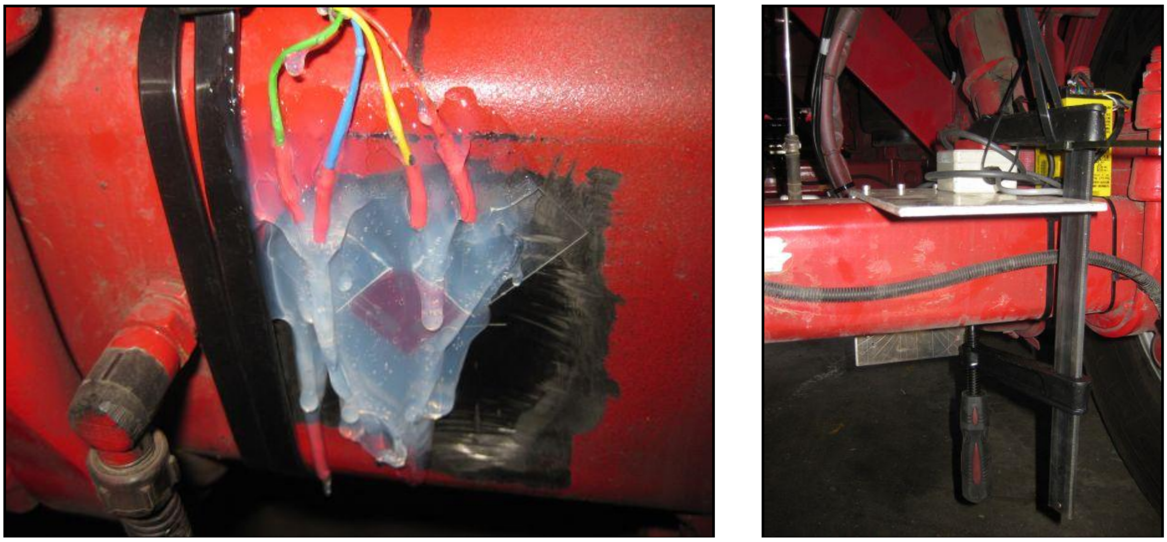

Figure 2 - Strain gauge and accelerometer measurement system

Traditionally, however, strain gauges have not been robust, and are generally used for limited measurement activities. Furthermore, strain gauges and accelerometers were originally ruled out due mainly to the relatively high costs and difficult installation process. However, since this project's inception in 2007, a number of advancements have been made with system components in the market. Coupled with this, refinements to the installation and usage procedures throughout this project were made, allowing this type of system to meet the criteria for a low-cost tool for accurately measuring dynamic wheel loads on a variety of vehicles.

2.3 Consideration of airbag pressure measurement in estimating dynamic wheel load

Although the strain gauge measurement system was considered the most viable, it was decided to undertake a preliminary investigation into another alternative, using airbag pressure measurements to estimate dynamic wheel loads.

Additional testing was conducted to compare the estimation of dynamic wheel loads from measurement of airbag pressures against those from the strain gauges with accelerometers system. The objectives of these tests were: to determine the degree of agreement between different measuring techniques; to determine the contribution of each load path to total vertical wheel load; to ascertain whether airbags can offer a cheaper means of measuring dynamic wheel loads with sufficient accuracy for research purposes; and to gain data on airbag forces to complete the picture of all force paths, in order to assist in validation of simulation models at a component level.

Two types of tests were undertaken: a drop test, where the trailer axle group was dropped suddenly through a distance of 80 mm; and an on-road test, where the trailer was towed along a circuit of public roads at 80 km/h.

These tests were repeated a number of times to establish the repeatability of measurements.

3. PRELIMINARY ANALYSIS OF DYNAMIC WHEEL LOADS

The main objective of the data collection phase of the first trial was to start to examine the differences between mechanical- and air-suspended trailers. The test program included trials of two vehicles along seven sections of road with varying roughness and length. The trials were conducted at 80 km/h and with two load configurations:

- laden, using Higher Mass Limits (HML)
- unladen.

3.1. Test vehicles

Two tri-axle semi-trailers, towed by a tandem drive Volvo FH520 prime mover, were used in these tests. To allow a comparison between different types of suspension, one trailer was a mechanical-suspended trailer approximately 20 years old (Figure 3a), and the other was an air-suspended trailer approximately 3 years old (Figure 3b). Both trailers were in good working order. The air-suspended trailer was reported to have well maintained shock absorbers, and the mechanical-suspended trailer was not fitted with any as part of the suspension design. Dynamic wheel loads were measured on the left and right wheel groups for the centre trailer axle only. In order to maintain a degree of control over the test environment, the same wheels and tyres were used on both trailers. The weights and run-outs of each were measured to help identify and remove these influences from the wheel-load measurements.

a. Mechanical suspension trailer

b. Air suspension trailer

Figure 3 - Trailers used in field trials

The gross combination masses (GCM) and axle group masses are listed in Table 2. The aim was for the trailer axle group loads as similar as possible for comparison.

Table 2 - Masses of test vehicles

Vehicle suspension and load configuration	Steer axle (t)	Drive (tandem) axle group (t)	Trailer (tri) axle group (t)	Gross vehicle mass (t)
Mechanical - unladen	5.96	6.24	4.92	17.12
Air – unladen	5.74	7.08	5.98	18.80
Mechanical - laden	6.04	9.44	17.04	32.52
Air – laden	5.96	12.48	16.66	35.10

3.2. Test sections

Testing was conducted on road sections at least 1 km long with three different levels of roughness designated ‘Smooth’ for International Roughness Indexes (IRI) of less than 2.3, ‘Medium’ for IRI between 2.3 and 3.8 and ‘Rough’ for an IRI greater than 3.8. The test roads had low traffic volumes, straight and flat sections and were located nearby to base facilities.

A survey of the road geometry was conducted by ARRB’s Network Survey Vehicle in order to determine the average lane IRI and Heavy vehicle Articulated Truck Index (HATI) (Hassan et al., 2006). A summary of the test sections is listed in Table 3.

Table 3 - Details for test road sections

Section ID	Section type	Length (km)	IRI	HATI
1	Rough	5.7	4.44	1.78
2	Rough	1.6	5.44	2.36
3	Rough	1.9	5.42	2.37*

4	Rough	5.4	4.48	2.16*
5	Smooth	1.8	1.85	0.85
6	Medium	1.7	2.96	1.45
7	Medium	1.5	2.99	1.50

* Some values were not available when calculating the section's average.

3.3. Analysis of results

An analysis of the strain gauge and accelerometer data was undertaken for each test section. A number of statistics, including Dynamic Load Coefficients (DLC) (Sweatman 1983) are reported to provide initial insights and comparisons. It should be noted that DLC is only one of a number of methods available for characterising dynamic wheel loads. It has limitations including:

- DLC measured at different static loads cannot be directly compared to evaluate the pavement impact (e.g. higher DLC when unladen than when laden should not be taken to indicate the dynamic wheel loads are greater when unladen or that their impact is greater).
- DLC does not provide a good measure of peak loads.
- DLC does not provide a measure of spatial repeatability of loads.

These limitations should be taken into account when considering the results.

3.4. Repeatability

It was of interest to examine the variance and repeatability of the data over a number of runs for the vehicles. Both test vehicles displayed very similar levels of repeatability, which provided a level of confidence in the system. As an example, the repeatability of the data is shown for the air-suspended semi-trailer on road Section 1 in Table 4. The 'left' and 'right' titled columns refer to the dual tyres on each side of the axle.

Table 4 - Comparison for two repeat runs of the air-suspended semi-trailer on Section 1

Results	Air-unladen				Air-laden			
	Run 1		Run 2		Run 1		Run 2	
	Left	Right	Left	Right	Left	Right	Left	Right
Mean (t)	1.247	1.247	1.247	1.247	3.027	3.027	3.027	3.027
Std. dev (t)	0.176	0.178	0.179	0.182	0.285	0.311	0.276	0.293
Min (t)	0.240	0.360	0.281	0.251	1.674	1.481	1.448	1.351
5th %ile (t)	0.964	0.960	0.958	0.954	2.568	2.531	2.580	2.557
Max (t)	2.433	2.273	2.592	2.255	4.681	4.657	4.672	4.632
95th %ile (t)	1.538	1.542	1.545	1.549	3.502	3.539	3.488	3.512
DLC	0.141	0.143	0.144	0.146	0.094	0.103	0.091	0.097
DLC (total)	0.142		0.145		0.098		0.094	

Some variance is seen in the minimum and maximum values. This is likely due to variations in the path followed by the vehicle, and the incidence of spikes in the data. Values for the 5th percentile and 95th percentile loads provide a much higher level of repeatability, as do the other statistics. During post-processing, the data offsets were normalised to the mean static loads.

3.5. Comparisons for test sections

The main area of interest for these trials was the comparison of results between the two test vehicles on each of the sections. A number of repeat runs were made, however the results are quite similar and only a single run for each vehicle and load configuration are listed in the following tables (Table 5 to Table 8) for select sections.

Table 5 lists the results for Section 2. Again, the mechanical-unladen vehicle recorded a slightly larger maximum (and 95th percentile) load than the air-unladen despite a lower static and mean load. In contrast, the mechanical-laden and air-laden results are very similar.

Table 5 - Dynamic load comparison for all vehicle/load configurations for Section 2 (Rough)

Results	Mechanical-unladen		Air-unladen		Mechanical-laden		Air-laden	
	Left	Right	Left	Right	Left	Right	Left	Right
Mean (t)	1.120	1.120	1.247	1.247	3.140	3.140	3.027	3.027
Std. dev (t)	0.365	0.418	0.196	0.201	0.353	0.432	0.343	0.383
Min (t)	-0.292	-0.847	0.448	0.441	1.611	1.591	1.376	1.213
5th %ile (t)	0.557	0.501	0.938	0.920	2.575	2.423	2.494	2.376
Max (t)	2.797	2.886	2.523	2.483	4.730	5.054	4.978	4.577
95th %ile (t)	1.773	1.923	1.575	1.590	3.728	3.840	3.608	3.655
DLC	0.326	0.373	0.157	0.162	0.112	0.138	0.113	0.126
DLC (total)	0.350		0.159		0.125		0.120	

Table 6 lists the results for Section 4. All vehicles displayed the greatest range of forces for this section compared to others.

Table 6 - Dynamic load comparison for all vehicle/load configurations for Section 4 (Rough)

Results	Mechanical-unladen		Air-unladen		Mechanical-laden		Air-laden	
	Left	Right	Left	Right	Left	Right	Left	Right
Mean (t)	1.120	1.120	1.247	1.247	3.140	3.140	3.026	3.028
Std. dev (t)	0.381	0.450	0.198	0.201	0.337	0.393	0.329	0.350
Min (t)	-0.944	-0.151	0.270	0.110	0.826	0.417	1.317	0.941
5th %ile (t)	0.523	0.461	0.932	0.929	2.622	2.539	2.504	2.482
Max (t)	3.237	3.107	2.823	2.611	6.006	6.373	5.057	5.415
95th %ile (t)	1.783	1.964	1.568	1.571	3.688	3.774	3.567	3.591
DLC	0.340	0.402	0.159	0.162	0.107	0.125	0.109	0.116
DLC (total)	0.371		0.160		0.116		0.112	

Table 7 lists the results for Section 5. The effect of the smoother pavement can clearly be seen with all vehicles displaying much lower wheel load ranges and DLC values.

Table 7 - Dynamic load comparison for all vehicle/load configurations for Section 5 (Smooth)

	Mechanical-unladen		**Air-unladen**		**Mechanical-laden**		**Air-laden**	
Results	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
Mean (t)	1.120	1.120	1.247	1.247	3.140	3.140	3.027	3.027
Std. dev (t)	0.169	0.180	0.110	0.103	0.199	0.235	0.171	0.186
Min (t)	-0.030	-0.487	0.451	0.498	2.189	2.178	2.193	2.136
5th %ile (t)	0.854	0.843	1.069	1.085	2.816	2.766	2.750	2.739
Max (t)	2.466	2.666	2.271	2.448	4.172	4.668	4.344	4.268
95th %ile (t)	1.391	1.400	1.419	1.413	3.461	3.524	3.299	3.341
DLC	0.151	0.160	0.088	0.083	0.063	0.075	0.057	0.061
DLC (total)	0.156		0.086		0.069		0.059	

Table 8 lists the results for Section 6. Similar patterns to previous sections are exhibited. As expected, the ranges for this medium section lie within those of the smooth and rough sections.

Table 8 - Dynamic load comparison for all vehicle/load configurations for Section 6 (Medium)

	Mechanical-unladen		**Air-unladen**		**Mechanical-laden**		**Air-laden**	
Results	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
Mean (t)	1.120	1.120	1.247	1.247	3.140	3.140	3.027	3.027
Std. dev (t)	0.263	0.283	0.166	0.158	0.304	0.365	0.278	0.271
Min (t)	-0.671	-0.661	0.345	0.291	1.560	1.345	1.636	1.235
5th %ile (t)	0.698	0.664	0.985	0.995	2.668	2.594	2.592	2.560
Max (t)	2.852	2.698	2.106	2.272	4.831	5.273	4.677	4.440
95th %ile (t)	1.559	1.604	1.524	1.496	3.624	3.720	3.508	3.425
DLC	0.235	0.253	0.134	0.127	0.097	0.116	0.092	0.090
DLC (total)	0.244		0.130		0.107		0.091	

Some general trends appeared across all seven test sections. For instance, the right wheel groups consistently displayed higher DLC values, and a greater range of loads. This is likely due to the typical crossfall on the test sections sloping down to the left, thus slightly increasing the load on the right side of the vehicles. It was observed that the mechanical-laden vehicle generally produced the greatest range and highest maximum loads, with the exception of one section. The mechanical-suspended trailer in both loading conditions (though particularly in the unladen condition), generally produced a greater range of forces than the air-suspended trailer. The difference in load distribution and mass moments of inertia between the two trailers would likely have had an influence. The DLC values appeared to be sensitive to the road section roughness for all vehicles.

These observations are only preliminary and further research is needed to investigate and understand the relative performance of air and mechanical suspensions.

4. DLC, IRI and HATI

One objective was to investigate the correlation of the dynamic forces to various road characteristics. As a preliminary investigation, DLC was plotted against both IRI and HATI for 100 m and 1000 m bins. Figure 4 illustrates the plots for 100 m bins.

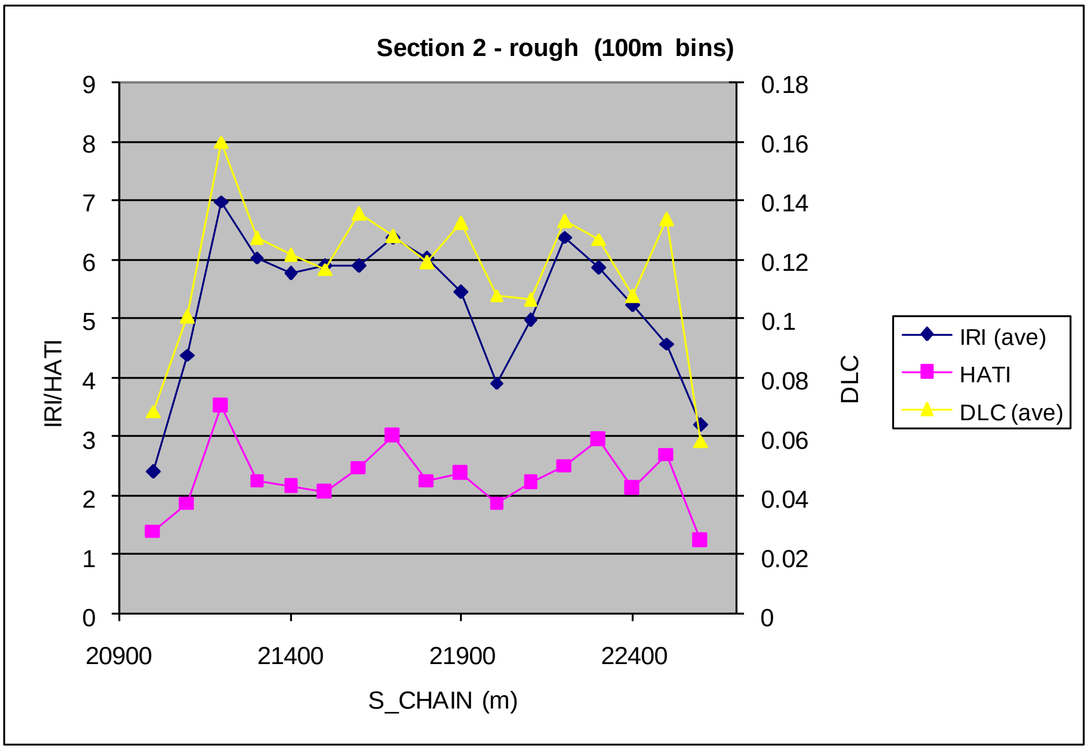

Figure 4 - DLC vs. IRI & HATI (100 m)

R^2 values for the linear regression equations of the relationship between DLC, IRI and HATI are summarised in Table 9Figure .

Table 9 - R^2 values for DLC vs. IRI & HATI regression equations

Signal	IRI		HATI	
	100 m	1000 m	100 m	1000 m
Strain gauges	0.86	0.98	0.91	0.99

It can be seen that the dynamic wheel loads showed a good correlation with both IRI and HATI. As expected, in all cases, using 1000 m bins provided a better correlation. The 100 m bins can contain quite volatile readings between consecutive bins. Given that the test vehicles were almost 20 m long and travelling at speeds of approximately 22 m/s (80 km/h), it is likely that the influence of the previous 100 m bin was still being experienced by the vehicle as it moved into the next bin, and therefore it appears 100 m long bins are too short to observe bin-specific effects. Synchronisation of the start and end points for both the DLC and IRI bins would also serve to reduce correlation. Alternatively, the 1000 m bins are long enough to smooth the volatility, reduce the effects of lack of synchronisation and allow bin-specific effects to be observed.

4.1. Dynamic wheel load estimation from airbags

Table 10 compares the correlation coefficient (R^2) for a full range of contributions to dynamic wheel force, for both drop and on-road tests.

Table 10: Correlation of different methods of estimating dynamic wheel load

Forces included in regression	Drop test (relative to load cells)	On-road Section 4 test (IRI = 4.48) (relative to strain gauge + inertia)
Airbags only	0.815	0.512
Airbag and damper (from string pot)	0.914	0.613
Airbag and damper (from airbags)	0.902	0.605
Airbag and damper and axle torque (from string pot)	0.937	0.777
Airbag and damper and axle torque (from airbag)	0.918	0.756
Axle force (from strain gauge)	0.970	0.760
Airbag, damper and axle torque (from string pot), and inertia	0.971	0.926
Airbag, damper and axle torque (from airbag), and inertia	0.954	0.887
Axle force (from strain gauge) and inertia	0.992	1

Figure 5 shows the contribution of each of these components during a drop test – this helps to visualise the improvement offered by including additional components. Note that damper and torque forces calculated using string pots are shown; the results when these forces are calculated using airbags are similar.

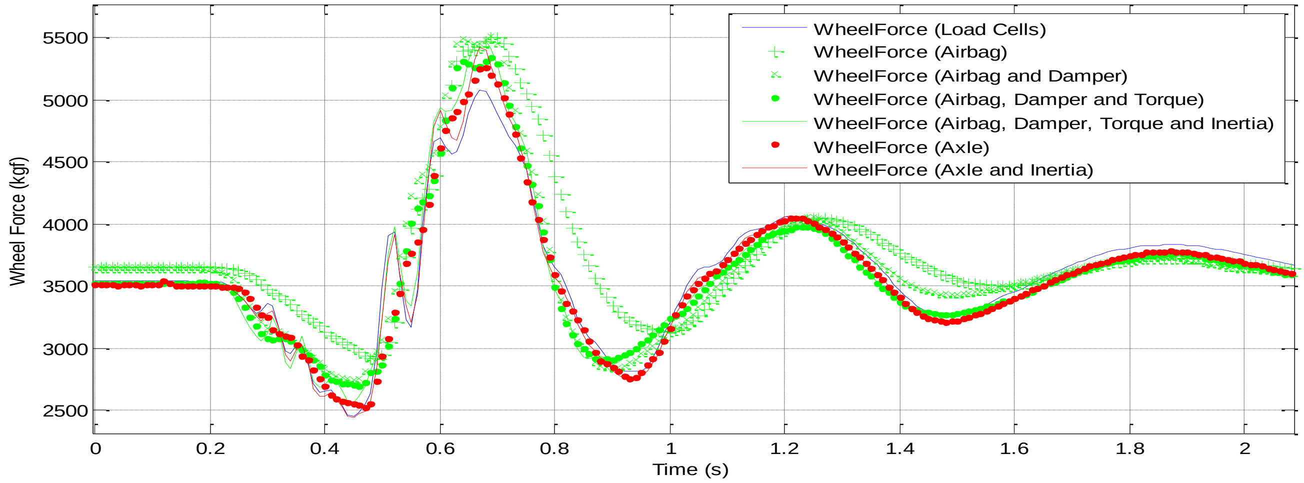

Figure 5: Dynamic wheel force on the right-hand wheel of the centre axle from drop test (time history) – damper and torque forces calculated using string pots

5. CONCLUSIONS

After considerable research, it was found that limitations in the laser transducer based method for estimating dynamic wheel loads could not be addressed whilst retaining the low cost, portable, and simple nature of the system. The more traditional and accepted method of using strain gauges with accelerometers, which offers relatively higher accuracy, was found to be more accurate, repeatable, cost effective and practical than a laser system modified to address its limitations.

The use of airbag pressure as an alternative measurement system was also investigated in the project. It was found that using airbag pressures has potential, but airbag pressures on their own are not an accurate indicator of dynamic wheel loads. Reasonably accurate results could be achieved by using airbag pressures in conjunction with other sensors and methods to estimate damper and hanger transmitted forces, however more research is required to understand the sensitivities of these types of measurement systems. The use of strain gauges and accelerometers was the recommended system.

Preliminary investigations into the relationships between dynamic wheel loads and the characteristics of the road and vehicle were undertaken, and the preliminary observations included:

- A high degree of correlation for a linear relationship between DLC and IRI, and DLC and HATI.
- The mechanical-suspended trailer in laden and unladen conditions generally appeared to produce a greater range of dynamic forces (in the on-road test sections) than the air-suspended trailer.

Further work on the investigation of the causal effects of dynamic wheel loads is soon to be commenced, with the objectives of increasing understanding on this topic and providing a predictive model that can be used to help inform pavement and structural responses, and ultimately inform infrastructure owners to better manage and maintain their networks.

6. REFERENCES

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