Article

Evaluation of the Impact of Timber Truck Configuration and Tare Weight on Payload Efficiency: An Australian Case Study

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Abstract: The forest industry tends to plan, and model transportation costs based on the potential payload benefits of increased legal gross vehicle weight (GVW) by deploying different configurations, while payload benefits of a configuration can be significantly influenced by the vehicle design tare weight. Through this research the relative benefit of increased legal GVW of different configurations is compared across Australia over a 13-year period from 2006 to 2019, by examining data collected post operation across multiple operations. This approach is intended to offer realistic insight to real operations not influenced by observation and thus reflect long-term operating behaviour. The inclusion of the three most common configuration classes in Australian forestry over a 13-year period has also allowed the exploration of load management between configurations and potential trends over time. When considering the legal GVW and the tare weight impacts across the fleets, the semi-trailer has an 8 t payload disadvantage compared to B-Doubles and 19.6 t disadvantage compared to road trains.

Keywords: transportation; payload; supply chain; configuration

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1. Introduction

While efficient planning and effective execution of every phase of the forest supply chain is economically important, the transportation phase tends to be one of the highest cost elements of the supply chain [1]. When modelling 10 supply chains for whole tree chips, Belbo and Talbot (2014) found transport costs that ranged from 13% to 24% of the total supply chain costs [2], while Ghaffariyan et al. (2013) found transport costs made up as much as 40% of the supply chain costs in forest residue supply chains in Western Australia [3]. For longer transport distances, the cost of transportation can exceed 40% [4]. The importance of payload to forestry transport is further demonstrated in Finland with the introduction of high capacity vehicles in 2013, where forest raw material had the highest uptake after 5 years, with over 90% of the freight task transitioned to the higher payload option [5]. More recent research has further demonstrated the environmental and CO₂ emissions efficiency the higher payload delivers [6,7]. As one of the highest cost elements in forest supply chains [8], it plays a significant role in the operational efficiency and ultimately the profitability of the forest supply chain.

A critical aspect of transport efficiency, including forestry transportation, is the net payload transported [9,10]. Considering the potential to increase payload to improve transport efficiency, Lukason et al. (2011) showed an increase of 8 t payload would reduce transportation costs by over 12% [11]. Within a given forest operation, there are a range of influences that can significantly impact the achieved payload. Some are constraints that are imposed by legislation and infrastructure, others are affected by medium- to long-term decisions about vehicle configuration and design, and actual load transported each trip can be affected by short-term operational and management decisions [12–14]. Typically, legislative and infrastructure limitations on payload are largely outside the control of a forest company or transportation contractor, while they have direct control over vehicle design, configurations, and operational payload management [15].

Vehicle configuration can have a significant impact on the potential net payload [16]. While infrastructure and legislation for the operating area influences what configurations can be selected and operated, other criteria will influence decisions about what configuration is deployed, such as the flexibility of the vehicle to work in different operations (i.e., deal with variation in road and infrastructure limits for the operating area), the range of products to be transported (i.e., set log lengths vs. variable log lengths for multiple markets), impact on other operating costs (i.e., common equipment across the fleet for service and maintenance efficiency), and impacts on operational complexity. Based on the legal gross vehicle weight (GVW), the potential payload difference for each configuration is clear, though this can be significantly influenced by the actual vehicle design and the empty or tare weight that is achieved by the design. Earlier research in Australia [17] found the range of tare weight operating within the same configuration varied by as much as 50%, where vehicles studied in the 79 t legal GVW road train configuration ranged from 24 to 36 t tare weight, changing the potential net payload by 12 t. While the average for the 79 t legal GVW road train configuration offered payload benefit over the lower legal GVW B-double configurations, those vehicle designs with higher tare weight lost this net payload benefit due to the heavier vehicle weight taking up more of the legal GVW limit. The range of vehicle design within the 79 t legal GVW road train configuration's more than 11 t benefit provided by the higher legal GVW of the road train configuration as compared to a B-double configurations was wiped out for heavier design road trains in the fleet as compared to some of the lightest vehicle designs in the lower legal GVW B-double configuration. This brings into question the actual net payload benefit for a particular configuration as compared to the potential benefit understood in the different legal GVW for the different configurations.

While the forest industry tends to plan and model transportation costs based on the potential payload benefits of increased legal GVW by deploying different configurations, research on specific operations has suggested that the difference can be significantly influenced by the vehicle design and operational payload management [15]. Through this research the relative benefit of increased legal GVW of different configurations was compared across Australia over a 13-year period from 2006 to 2019 by examining data collected post operation across multiple operations. While each configuration has a national legal GVW, local infrastructure and state government legislation may restrict the legal GVW for a particular route or region or may offer a higher legal GVW for particularly important commercial routes that can support the increased load safely. Variation noted in the legal GVW for each configuration is a result of some of the forest operations that contributed data across different local limits from time to time, as opposed to any technical difference in vehicle design (i.e., number of axles). This approach is intended to offer realistic insight into real operations not influenced by observation and thus reflect long-term operating behaviour. The inclusion of the three most common configuration classes in Australian forestry over a 13-year period has also allowed the exploration of load management between configurations and potential trends over time.

2. Materials and Methods

2.1. Data Collection

Historical data were collected from active forest operations without prior notice to the operators that the payload was being monitored. The dataset includes both roundwood and wood chip transportation operations from both pine and Eucalyptus plantation operations, all of which were operating under the same weight regulations. The data were sourced voluntarily from a range of different operations in New South Wales, Victoria, South Australia, and Western Australia. The data were collected randomly from the cooperating operations for the period between 2006 to 2019. The datasets included direct measurement by trip of the tare weight and GVW for each trip and net payload was determined by subtracting the tare weight from the GVW recorded. The data were deidentified for the companies, operators, and states, and categorized by configuration based on their legal

GVW as provided by the operations managers where the data was sourced. The data were then examined and outliers and corrupted entries (weight recorded was less than 60% of the legal GVW—i.e., half loads and those missing fields) were removed from the analysis, GVW that exceeded the legal GVW were retained for the analysis. The smallest configuration included were semi-trailer configurations with legal GVW ranging from 39 t up to 57.5 t, B-double configurations with legal GVW ranging from 62.5 t up to 68 t, and road train configurations with legal GVW ranging from 79 t up to 83 t, as shown in Table 1 and Figure 1. A total of 75,996 individual loads were included in this analysis.

Table 1. Overall length and legal GVW for different truck configurations.

	Semi-Trailer	B-Double	Road Train
Overall length (m)	19	25	36.5
Standard Legal GVW (t)	42	62.5	79
Legal GVW range due to localized allowance or restrictions (t)	39.0–57.5	62.5–68.0	79.0–94.5

Figure 1. Vehicle configuration descriptions.

2.2. Statistical Analysis

A frequency histogram of the net payload and vehicle tare data was prepared in SPSS 21 (<https://www.ibm.com/products/spss-statistics> (accessed on 4 May 2021)) for each configuration. A Kolmogorov–Smirnov test determined the data were not normally distributed. Therefore, a nonparametric test, Kruskal–Wallis H test (one-way ANOVA on ranks), was applied to test the hypothesis of equality of the medians of net payload and vehicle tare for each configuration.

The Kruskal–Wallis H-Test for one-way analysis of variance by Ranks is the non-parametric equivalent of the parametric one-way analysis of variance (ANOVA). Both the Kruskal–Wallis Test and one-way ANOVA are used to determine if there are statistically significant differences for comparisons of three or more groups. The Kruskal–Wallis Test is used with ranked data, particularly when there are concerns about deviation from normal distribution and there is a considerable difference in the number of subjects for each comparative group [18].

To allow simple comparison between the distributions to determine how symmetrical the distributions are and how tightly the distributions are grouped for each configuration, boxplots displaying the distribution of data based on minimum, first quartile, median, third quartile, and maximum were used [19].

The statistical significance level of 5% ($\alpha = 0.05$) was applied in the data analysis. The null hypothesis could be expressed as follows:

H0: Average net payload of semi-trailer configurations = Average net payload of B-Double configurations = Average net payload of road train and Average tare weight of semi-trailer configurations = Average tare weight of B-Double configurations = Average tare weight of road train configurations.

This null hypothesis was set to explore how important an influence vehicle tare weight design is relative to the actual increased legal GVW that larger configurations theoretically offer before the introduction of operational management strategies to maximize payload.

Correlation was then tested with Spearman's rank correlation coefficient test, which is a nonparametric measure of rank correlation and can determine the correlation between two variables using a monotonic function.

2.3. Transport Cost Modelling

Using the mean tare weight and legal GVW for each configuration, indicative transportation costs were calculated for 10 km haul distance increments between 50 and 150 km and compared with costs for the maximum and minimum tare for each configuration. It was assumed each haul distance included 5 km of gravel roads in the total haul distance with the balance being paved public roads, which is typical for Australian plantation operations. Where the primary interest was to explore the relative difference in transportation costs as a result of the payload, a simple spreadsheet costing model with indicative costs were used based on the indicative costing information presented in Table 2. Travel speed was modelled on paved roads at 80 km/h loaded and 85 km/h empty, while the short gravel sections were modelled as 20 km/h loaded and 25 km/h empty. A generic salvage value of 10% was used for the tractor after a 5-year life and for the trailer after a 10-year life with simple straight-line depreciation, and a discount or interest rate of 10% was assumed for the model. Costings were calculated on an annual basis for a given haul distance to determine an average transport cost per ton transported for each increment of 10 km haul distance:

$$AW = W \times OH$$

$$L = PH / (2 \times HD / AS)$$

$$D = L \times 2 \times HD$$

$$M = D \times MC$$

$$F = (15 + 1.06 \times GVW \times (DPL/100)) + (15 + 1.06 \times Tare \times (DPE/100)) + (11 + 2.03 \times GVW \times (DGL/100)) + (11 + 2.03 \times Tare \times (DGE/100))$$

$$FC = F \times FP$$

$$AC = AW + M + F + AF$$

$$AT = L \times (\text{legal GVW} - \text{Tare})$$

$$TR = AC / AT$$

where:

AW = Annual wage costs (AU\$)

W = wages including benefits (AU\$)

OH = Operating hours per year (h)

L = Loads transported per year

PH = Annual productive hours (h)

HD = one-way haul distance (km/trip)

AS = Average travel speed (km/h)

D = Annual distance (km)

M = Annual maintenance costs (AU\$)

MC = Maintenance cost (AU\$/km)

F = Annual fuel use (L)
 GVW = average gross vehicle weight (t)
 DPL = Annual distance on paved roads loaded (km)
 DPE = Annual distance on paved roads empty (km)
 Tare = average tare weight (t)
 DGL = Annual distance on gravel roads loaded (km)
 DGE = Annual distance on gravel roads empty (km)
 FC = Annual fuel cost
 FP = Fuel price (AU\$/L)
 AC = Total annual costs (AU\$/yr)
 AF = Annual fixed costs and overheads (AU\$/yr)
 AT = Annual transported tonnage (t/yr)
 TR = Transportation rate (AU\$/t)

Table 2. Typical Australian indicative industrial transport costing parameters.

Cost Element	Semi-Trailer	B-Double	Road Train
Wages including benefits (AU\$/hr)	72	72	72
Operating hours per year	2760	2760	2760
Annual productive hours	2491	2491	2491
Avg load/unload time (min)	50	80	90
Fuel price (AU\$/L)	1.35	1.35	1.35
Maintenance (AU\$/km)	0.45	0.50	0.55
Annual fixed costs and overheads (AU\$/yr)	150,000	160,000	170,000

3. Results

The descriptive statistics of the net payload, vehicle tare, and net overloads of each configuration are presented in Table 3. Of the total dataset of 75,996 loads analysed, 31,374 loads were transported by road trains, 18,243 loads by B-double, and 26,379 loads by semi-trailers.

Table 3. Descriptive statistics of recorded parameters for each truck load by configuration.

Configuration	Metric	Gross	Legal GVW	Vehicle Tare	Net Payload
Semi-Trailer	Mean (t)	47.84	50.19	17.92	29.92
	Std. Dev.	46.50	59.86	11.62	38.85
	Min (t)	35.04	39.00	12.00	15.78
	Max (t)	59.80	57.50	20.80	41.15
B-Double	Mean (t)	66.00	62.93	22.61	43.39
	Std. Dev.	21.96	14.66	14.35	27.85
	Min (t)	59.00	62.50	16.80	32.02
	Max (t)	74.96	68.00	27.50	50.90
Road Train	Mean	80.13	80.61	28.77	51.35
	Std. Dev.	40.74	32.24	25.00	49.89
	Min	67.58	72.00	22.40	37.22
	Max	99.95	94.50	36.98	70.20
Total	Mean	65.53	65.81	23.53	42.00
	Std. Dev.	145.65	139.42	51.01	102.28
	Min	35.04	39.00	12.00	15.78
	Max	99.95	94.50	36.98	70.20

The data for net payload and vehicle tare for each configuration were tested for normal distribution and both were found to be not normally distributed as per the results of the Kolmogorov–Smirnov test shown in Table 4.

Table 4. Kolmogorov–Smirnov test results.

Parameter	Configuration	Kolmogorov—Smirnova		
		Statistic	df	Sig.
Net Payload	Semi-Trailer	0.091	26,379	0.00
	B-Double	0.059	18,243	0.00
	Road Train	0.025	31,374	0.00
Vehicle Tare	Semi-Trailer	0.155	26,379	0.00
	B-Double	0.078	18,243	0.00
	Road Train	0.080	31,374	0.00

The null hypothesis was rejected because there were significant differences among at least two means of net payload and vehicle tare for the different configurations (Table 5) using the Kruskal–Wallis test, with a similar rejection of the null hypothesis confirmed by samples median tests.

Table 5. Kurskal–Wallis test results.

Test	Parameter	Sig.
Independent samples Kruskal–Wallis test	Net Payload	0.00
	Vehicle Tare	0.00
Independent Samples Median test	Net Payload	0.00
	Vehicle Tare	0.00

For all three pairwise comparisons, the null hypothesis was rejected, which indicated that each configuration had different distributions for their tare weight as shown in Table 6. Box plots of the tare weight distribution for each configuration show the greatest spread of tare weight for the road train configurations, with both the road trains and B-doubles slightly skewed to the lower end of the tare weight range and the semi-trailers skewed to the upper end of the range (Figure 2).

Table 6. Tare weight pairwise comparison of configurations for being the same distribution.

Configuration Pair	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Semi-Trailer vs. B-Double	−22,562.1	211.3	−106.8	0.00	0.00
Semi-Trailer vs. Road Train	−46,961.3	183.3	−256.3	0.00	0.00
B-Double vs. Road Train	−24,399.1	204.3	−119.5	0.00	0.00

As for tare weight, the null hypothesis was rejected for net payload for all configuration comparisons, indicating they are all independent distributions (Table 7). The box plots (Figure 3) further demonstrate the difference between the three distributions, with road trains and B-double showing little or no skewness. The semi- skewed to the upper portion of their net payload range.

Figure 2. Tare weight statistical characteristics box plot of independent samples Kruskal–Wallis Test.

Table 7. Net payload pairwise comparison of configurations for being the same distribution.

Configuration Pair	Test Statistic	Std. Error	Std. Test Statistic	Sig.	Adj. Sig.
Semi-Trailer vs. B-Double	−24,646.3	211.3	−116.7	0.00	0.00
Semi-Trailer vs. Road Train	−45,662.9	183.3	−249.2	0.00	0.00
B-Double vs. Road Train	−21,016.6	204.3	−102.9	0.00	0.00

Based on the results, the semi-trailer configuration had the lowest net payload and tare weight, while the road train configuration had the highest net payload and tare weight, with the B-double configuration sitting between the semi-trailer and road train configuration for these parameters.

The Spearman’s rank correlation test results (Table 8) show a strong positive correlation between configuration, tare weight, and net weight. In all cases, the correlation is strong and statistically significant.

Figure 3. Net payload statistical characteristics box plot of independent samples Kruskal–Wallis Test.

Table 8. Spearman’s rho test results.

Parameter	Metric	Configuration	Tare Weight	Net Weight
Configuration	Correlation coefficient	–	0.931 **	0.902 **
	Sig. (2-tailed)		0.000	0.000
Tare Weight	Correlation coefficient	0.931 **	–	0.795 **
	Sig. (2-tailed)	0.000		0.000
Net Weight	Correlation coefficient	0.902 **	0.795 **	–
	Sig. (2-tailed)	0.000	0.000	

** Correlation is significant at the 0.01 level (2-tailed) N = 75,996.

To provide an economic perspective on the impact, indicative costs in AU\$ were modelled over a transport distance of 50 to 150 km for the three configurations considering the potential payload relative to the highest, lowest, and mean tare weights (Figure 4).

Figure 4. Indicative transportation costs by transport distance for tare weight and legal GVW recorded.

4. Discussion

The large datasets spread over more than a decade provide a high-level perspective on how perceived transport efficiencies offered by higher legal GVW configurations are realized in practice for Australian forest transport operations as a result of vehicle design (tare weight). Mean semi-trailer legal GVW, tare, and load weights were similar to those reported by Trzinski et al. [20]. International comparisons with B-double and road train weights were not possible as there were no published data for these truck configurations. As it was somewhat anticipated, both the semi-trailer and the road train had the greatest variation in vehicle tare as the configurations that tend to be more customized to a local condition or task, while the B-double is more standard across the country. In the case of semi-trailers, for many operations, they work amongst a bigger fleet of B-doubles and/or road trains as a more versatile option to deal with sites or loads outside the operating capacity of the larger vehicles. Road trains also tend to be customized to a specific operator or task in larger operations with routes and locations suited to the larger vehicle.

Based simply on the legal GVW of each of the configurations analysed, B-doubles would have a 5 to 29 t payload advantage on a semi-trailer (12.7 t based on the fleet means), and road trains would have a 22.5 to 44 t advantage on a semi-trailer (30.4 t based on the fleet means) (Table 2).

The tare mass of a truck depends on axle configuration, truck body and drive terrain type, material types used for manufacturing, on-board equipment, and fuel [21]. The

B-double and the road train, having longer trailer frames, more axles, and larger trucks to pull heavier weights, tend to have heavier tare weights but material types and on board equipment can be selected towards a lighter design (e.g., plastic mudguards, aluminum rims, bolsters and bull bars) and reduce how much of the legal GVW advantage is taken up by added vehicle tare weight. In the case of the road trains, the lowest tare weight recorded in the dataset was 22.4 t, which is only slightly higher than the heaviest semi-trailer at 20.8 t and is lighter than the heaviest B-double (27.5 t). When compared based on mean tare weights, the 12.7 t advantage the B-double had on the semi-trailer based on legal GVW was reduced to 8 t, while the 30.4 t advantage for the road train was reduced to 19.6 t.

These mean tares for the fleet were consistent with those recorded in a study conducted by Cooperative Research Centre (CRC) for Forestry in Australia in 2008 [17]. In the 2008 study, it was suggested that, while targeting the lightest tare in the fleet may not be a reasonable industry objective, targeting the mean of the lightest 20% in an active fleet still represented a significant improvement of about 2 t for semi-trailers, 1.5 t for B-doubles, and just over 2 t for road trains. The 1.5 to 2 t reduction in tare weight for the fleets that were analysed in this study would represent a 4% to 7% potential increase in transport productivity. Taking the more extreme view of potential efficiency gains based on the minimum tare weights recorded in the fleets studied, the B-double and road train configurations would result in approximately 13.7% potential improvement in payload, and nearly 20% for semi-trailers.

When considering the indicative modelled transport costs, such as other published modelled transport costs, the relative importance of increased payload becomes more important for longer transport distances [3,22,23]. In Figure 4, the maximum payload condition (lowest tare) is a similar payload to the average B-double and they present as nearly parallel lines even with 60% more time allocation for loading and unloading the B-double configuration. The road train operating with the lowest tare weight on the 50 km haul distances was 34% of the transport cost of the heaviest semi-trailer operating on the 150 km haul distance. As a highlight of the combined role of the legal GVW available to a configuration and the tare weight in the potential payload and overall efficiency, the indicative cost comparisons show the lightest semi-trailers and B-doubles offer a similar relative cost to the mean road trains at shorter haul distances. The study results demonstrated that configuration plays an important role in payload management and thus transportation efficiency, and is consistent with results presented by Reddish et al. [24] and Hamsley et al. [10].

5. Conclusions

Even with the impact of increased mean vehicle tare weight in the fleets, to safely accommodate the increased legal GVW, B-doubles delivered a 42.4% increase in payload over the semi-trailer, and the road train offered a further 40.8% over the B-double or 101.7% over the semi-trailer. It can also be seen that the vehicle tare weight can vary significantly as a result of vehicle design within the given configurations. Lower tare weights could result in substantial reductions in transport costs and hence in delivered costs of logs and chips. Further research could explore opportunities to optimize these designs based on applied industry experience. Future studies could also explore the impacts on performance, safety, and maintenance costs of deploying lighter designed vehicles for improved payload efficiency.

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